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PHOSPHORUS RECOVERY FOR FERTILISERS FROM DAIRY WASTEWATER - SUSTAINABILITY ASSESSMENT AT EARLY STAGES OF TECHNOLOGY DEVELOPMENT

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Gothenburg, Sweden 2022

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PHOSPHORUS RECOVERY FOR FERTILISERS FROM DAIRY WASTEWATER – SUSTAINABILITY ASSESSMENT AT EARLY STAGES OF TECHNOLOGY DEVELOPMENT

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ABSTRACT

A reduction in the availability of phosphate rock resources for fertiliser production coincides with an increase in phosphorus-rich dairy wastewater in Europe. This confluence of events has led to the development of technologies for phosphorus recovery from dairy wastewater and the use of the products as fertilisers in agriculture. This thesis aims to contribute both to the technical development of this emerging technical system and methodological development of assessing the sustainability of it with regard to (1) the identification and selection of sustainability indicators, and (2) the assessment of life cycle environmental impacts. The thesis describes an approach developed for identifying and selecting sustainability indicators by reviewing scientific documents and interviews as well as an approach employed for performing a meta-analysis of previously published life cycle assessment results to cope with lack of inventory data. The employed method for indicator selection narrows down an initial set of 382 sustainability indicators identified in the literature to 26, which were considered representative and useful for the assessment of the considered innovative conceptual system. The meta-analysis results suggested that the examined phosphorus recovery technologies exhibited a lower global warming potential and cumulative energy demand than those of dairy wastewater treatment processes and that those technologies recovering phosphorus from the liquid phase had lower impacts than those recovering phosphorus from sludge or ash.

Keywords: phosphorus recovery, dairy wastewater, wastewater treatment, LCA, environmental impacts, sustainability, meta-analysis, indicator, screening

LIST OF PUBLICATIONS

This thesis is primarily based on the work described in the following two papers:

PAPER I
Behjat, M., Svanström, M., Peters, G., Perez-Soba, M.: Sustainability indicator identification and selection for an innovative conceptual system: phosphorus recovery from dairy wastewater (submitted and under review).

PAPER II
Behjat, M., Svanström, M., Peters, G. (2022). A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater. Journal of Cleaner Production. 369, 133307.
https://doi.org/10.1016/j.jclepro.2022.133307

Other related publications:

PUBLICATION A
Behjat, M., Svanström, M. (April 2020). A review of LCAs studies analysing dairy processing water treatment and P-recovery technologies. Chapter in deliverable 3.1 - Literature reviews of each research area in WP3.

PUBLICATION B
Behjat, M., Svanström, M. (June 2021) Deliverable 3.6 - Report on first stage environmental assessment for project guidance.

PUBLICATION C
Behjat, M., Svanström, M., Peters, G. (21-25 June 2021). A review on environmental impact of dairy wastewater treatment and the prospect for P-recovery from an LCA perspective. Online poster presentation presented at the 5th IWA – ecoSTP, Milan Italy.

PUBLICATION D
Behjat, M., Svanström, M., Peters, G. (29 October 2021). Environmental assessment of a conceptual system for phosphorus recovery from dairy wastewater. Online presentation presented at the NORDIWA, Gothenburg, Sweden.

PUBLICATION E
Behjat, M., Svanström, M., Peters, G. (22 June 2022). Environmental assessment of a conceptual system: phosphorus recovery from dairy wastewater. Presentation presented at the PERM5, Vienna, Austria.

PUBLICATION F
Behjat, M., Svanström, M. (September 2022) Deliverable 3.4 - Indicators for communication of sustainability of DPW fertilizer products

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LIST OF ABBREVIATIONS AND CHEMICALS

Abbreviations	
A	Ash
AD	Anaerobic digestion
AnMBR + FC	Anaerobic membrane reactor combined with freeze concentration
AP	Acidification potential
CE	Circular economy
CED	Cumulative energy demand
DWW	Dairy wastewater
DWWT	Dairy wastewater treatment
EC	European Commission
EDA	European dairy association
EEA	European environmental agency
ETN	European training network
EU	European Union
FU	Functional unit
GHG	Greenhouse gases
GWP	Global warming potential
HTC	Hydrothermal carbonization
ISO	International organization for standards
JRC	Joint research centre
L	Liquid
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
MCA	Multicriteria analysis
PM	Particulate Matter
RA	Research area
RQ	Research question
S	Sludge
SBR - EBPR	Sequencing Batch Reactor- Enhanced Biological Phosphorus Removal
S-LCA	Social life cycle assessment
SM	Supplementary material
TP	Total phosphorus
UN	United Nations
WWT	Wastewater treatment

List of Chemicals	
CaC_2O_5	Calcium dicarbonate
DCP	Dicalcium phosphate
FeC_2O_4	Ferrous oxalate
$MgCl_2$	Magnesium chloride
H_3PO_4	Phosphoric acid
P	Phosphorus
NaOH	Sodium hydroxide
H_2SO_4	Sulfuric acid

1 INTRODUCTION

Phosphorus (P) is a chemical element present in every living cell, vital for life as part of the molecule *adenosine triphosphate* and the phosphorylation reactions that are the basis of energy transportation and conversion within plants and animals (Filippelli, 2008).

In abiotic systems, P does not occur naturally other than in the form of phosphate rock. Phosphate rock is a finite, non-renewable resource that is largely needed for fertiliser production. The lack of exploitable phosphate mineral reserves in Europe (Schröder et al., 2010), combined with the general scarcity and the increasing global demand for this material, poses a threat to the European food security. This looming P crisis has led the European Commission to the inclusion of this resource in the critical raw material list in 2014 (European Commission, 2020) as well as to the exploration of alternatives to phosphate rock for fertiliser production.

Therefore, considering its importance and scarcity, the European Union (EU) has prioritised the recovery and safe reuse of P from food and municipal waste flows through its circular economy package (European Commission, 2016).

As a result, interest in the development of technologies with regard to nutrient recovery from organic waste streams has increased recently. A potential input waste stream for these technologies is dairy wastewater (DWW). Therefore, an emerging technology combines DWW treatment (DWWT) with the recovery of P-rich products for such products to be used as fertilisers in agricultural activities. This technology, however, remains in the early stages of its process and market development, and production data are presently unavailable. The purpose of this research was to contribute to both the technical development and methodological development of assessing the sustainability of this innovative technology. This situation is occasionally described as the Collingridge Dilemma: when the system that is intended to be assessed has not yet been fully developed and become utilized, the impacts are difficult to predict, while changes become more difficult when the system becomes better described but more entrenched (Collingridge, 1982).

This thesis provides guidance on methods to partially overcome the lack of information by contributing to (1) the selection of a broad range of sustainability indicators for assessing impacts of the recovery system of P from DWW to produce fertilisers for agricultural activities and to (2) the environmental assessment by a meta-analysis, or rather, the mining and refining of information from previous life cycle assessment (LCA) studies.

2 BACKGROUND

2.1 The REFLOW project

This research was conducted within the REFLOW European Training Network (ETN) project: P Recovery for Fertilisers from Dairy Waste (January 2019–December 2023). The project received funding from the European Union Horizon 2020 (Grant Agreement number 814258), under the Marie Skłodowska-Curie Actions program. The work described in this thesis was performed within a work package that dealt with the environmental and techno-economic performance of the P-rich products recovery system (Figure 1). The purpose was to guide development in the project consortium toward economic and environmental sustainability. As there was no full-scale production technology of P-rich products from the treatment of DWW yet, a future-oriented assessment approach using different explorative scenarios in combination with close collaboration with the technology developers within the project was needed. The focus of the collaboration was on collecting data and information for the sustainability assessment and delivering results helpful for guiding the development of the technologies.

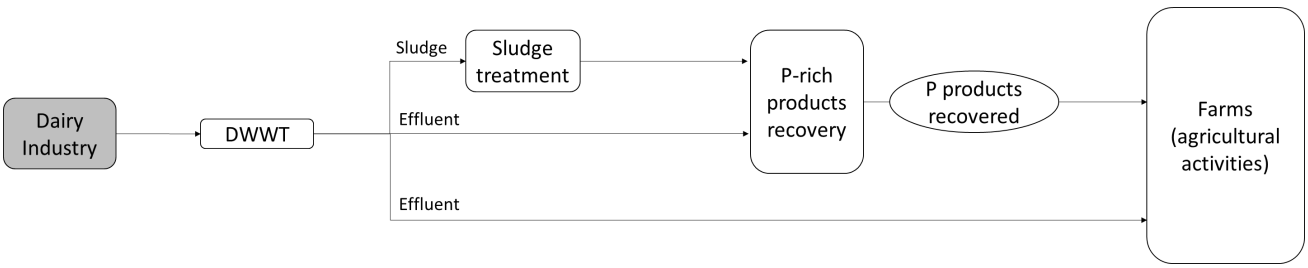


Figure 1 Generic representation of the REFLOW system with recovery of phosphorus products from dairy wastewater, DWWT= Dairy wastewater treatment. The process in the grey box (dairy industry) is not included in the assessment.

2.2 Phosphorus as a critical raw material

Several forms of phosphate exist naturally, but the form mainly used for human activities is enclosed in minerals referred to as phosphate rock. In phosphate rock, P is present in an appreciable concentration, and its main form is fluorapatite (Filippelli, 2008). Phosphate rock deposits are not equally distributed throughout the globe, and there is only one mine in Europe, which is located in Finland. Finland is therefore unique in Europe in its supply of phosphate rock (Smol et al., 2020), but it constitutes less than 1% of the world's total production (European Commission, 2017). Two thirds of the world production is controlled by Morocco, the USA and China (Reijnders, 2014). In Europe, phosphate rock is primarily used for the production of fertiliser. Fertiliser demand is expected to increase owing to an increasing global population and consequent increase in food demand. From 1983

to 2013, the global consumption of phosphate rock increased by 25% (Bradford-Hartke et al., 2015). The increasing demand for this finite resource has 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, 2017). Phosphate rock is identified as non-substitutable and of high economic importance. Within the proposed revised EC Fertilizer Regulations, the purpose of which is to align the market for products produced using recycled P and mineral fertilisers, the EU Commission tasked the Joint Research Centre (JRC) to undertake an assessment of potential candidate materials for inclusion in recycled fertiliser products and to provide guidelines for their processing and quality. The interim STRUBIAS report (2017) nominated materials containing STRUvite (recovered phosphate salts), BIochar (including hydrochar), or incineration AShes as suitable candidates (Huygens et al., 2019). REFLOW targets these materials as fertiliser components.

2.3 Circular economy package

European policies target the efficiency of material use and recycling, waste policies, and international cooperation to address raw materials' criticality and dependency. The reuse of waste as raw materials is one of the key principles of the Circular Economy (CE) Action Plan presented by the European Commission in March 2020 (European Parliament, 2022). The EU started to prioritise the recovery and safe reuse of P from food and municipal waste flows through its CE package in 2016 (European Commission, 2016). "The CE is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended" (European Parliament, 2022). The "use as resource" element of the CE is supported by the updated EU rules on fertiliser products, known as Regulation 2019/1009. The updated version lays down an exhaustive list of materials allowed in fertilising products. The list includes precipitated phosphate salts, such as struvite, and derivatives, such as ashes and biochar.

2.4 Dairy industry

The dairy industry is the most economically important sector of the European agri-food industry, and it is present in all EU member states (EDA, 2018). It provides nutrition to all generations of the European population and regular earnings to 300.000 employees in dairy companies, and 700.000 farmers producing raw milk (EDA, 2018). The total EU milk production is approximately 160 million tons (22% of the world's total milk production) (EDA, 2018). The EU is a major exporter of dairy products and the largest cheese and skimmed milk powder exporter in the world (EDA, 2018). In 1984 the European milk quota system was introduced to limit public expenditure on the sector, control milk

production, and stabilise milk prices and agricultural income of milk producers (European Commission, 2009). After the system was abolished in 2015, the dairy sector grew (Slavov, 2017), and higher DWW volumes need to be treated to avoid environmental problems (Ashekuzzaman et al., 2019). The wastewater generated in dairy industries comprises different types of effluents: wastewater from the production line (cleaning of equipment and pipes), cooling water, and whey. The DWW often contains large quantities of milk constituents, such as casein, inorganic salts, besides detergents and sanitizers used for washing. All these components contribute largely toward its high biological oxygen demand and chemical oxygen demand. The whey forms the most polluting effluent by its biochemical composition rich in organic matter. The presence of organic matter in the DWW leads to eutrophication, which, among other things, involves the growth of cyanobacteria (blue-green algae), that consume oxygen by feeding on N and P in lakes and oceans (Vaccari, 2009). Eventually, it results in the oxygen depletion of waters, leading to the gradual depletion of fish. Therefore, there is a need to treat dairy effluents by various processes (Raghunath et al., 2016). However, DWW, other than being a challenge, is also an essential resource. DWW is a potential source of P (Yapıcıoğlu and Yeşilnacar, 2020) that could contribute to addressing the growing demand for fertilisers for food production. As individual dairy industry facilities have very different product portfolios, the characteristics of DWW effluents vary greatly, but the P concentration is typically higher in DWW than in municipal wastewater (Shilpi et al., 2018). The concentration of total P (TP) in DWW has been reported to vary from 8 to 280 mg/L (Demirel et al., 2005), and sludge produced from DWW treatment has been reported to have a content as high as 52 g TP/kg of sludge (Numviyimana et al., 2022).

2.5 Challenges for assessing the sustainability of emerging systems

Sustainability can be effectively integrated into the development process. According to Sartorius (2005), sustainability is considered as a development in which three kinds of interests are met simultaneously: environmental, economic, and social sustainability. The first interest concerns the needs of the future generation: the current generation should not have an impact on the needs of the future one. The second interest involves the present generation improving their living conditions. The final interest involves the search for an equalisation of the living conditions within society. Various other useful descriptions of sustainability dimensions exist in literature and in policy documents, e.g. the “Europe Sustainable Development Report 2021”. This report describes ways to monitor and address socio-economic and environmental impacts through the entire supply chains by supporting the food companies in adapting sustainability principles at the management level.

Sustainability indicators and LCA are common tools used to assess the sustainability of technical systems, also emerging ones although access to data then often becomes a limitation. As previously discussed, the emerging system under study here, which combines DWWT with P recovery, remains rather unexplored and is by no means mature. The availability of data is therefore a problem due to the lack of detailed information about the involved technologies. The lack of this information and knowledge on which specific indicators to be used are major challenges in assessing the sustainability of this emerging technology.

2.6 Sustainability indicators

Sustainability indicators represent important sources of information for different steps in the policy- and decision-making process (Frederiksen and Kristensen, 2008). According to the European Environment Agency (EEA), an indicator is "a measure, generally quantitative, that can be used to illustrate and communicate complex phenomena simply, including trends and progress over time" (EEA, 2005). Indicators are useful tools for the development and evaluation of policies and for decision-making. Sets of these kinds of indicators are now commonplace in national policy-settings for sustainable development (Frederiksen and Kristensen, 2008).

Despite a vast number of indicators or indicator sets being available, the use and influence of indicators may still be weak (Gudmundsson, 2003; Rosenström and Kyllönen, 2007). This is due to the fact that "the direct use of indicators by decision-makers is the only way of using indicators, and that the indicators may play a lesser role than would be expected from the many justification stated at the time of indicator development" (Frederiksen and Kristensen, 2008). However, tools for prioritizing sustainability indicators during the sustainability assessment of a production system, have been developed and proposed. For a set of sustainability indicators to cover the broad range of concerns that may be important, they should potentially span over all the "interests" as were described by Sartorius (2005) as environmental, economic, and social. In the context of this thesis, with its focus on providing decision-support to actors working on the development of an early-stage technical system, the economic indicators were reframed slightly and replaced with the term "techno-economic" indicators. These techno-economic indicators describe and estimate the performance and costs of the industrial system at an early-stage prior to its development (Liu et al., 2018). Environmental indicators describe the human pressure on the environment and the state of the environmental compartments (air, water and soil) after the use of resources, changes in land use, and emissions (EEA, 2000). Social indicators describe the condition of specific social aspects with respect to a set of values and goals (UNEP, 2009).

These indicators are used to measure progress towards the policy objectives, but can also describe the present situation and main challenges for poverty and social exclusion policies (EEA, 2004).

2.7 LCA

LCA is a method for assessing potential environmental impacts of a product life cycle, from raw material acquisition through production, use, recycling, and final disposal (ISO 14044, 2006). The LCA method is described in the international standard ISO 14044. On the basis of this standard, an LCA study consists of four phases (see Figure 2) (ISO 14040, 2006).

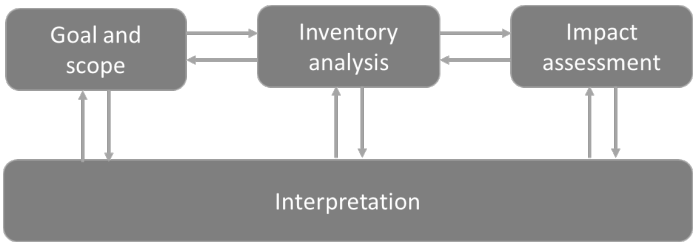


Figure 2 The LCA procedure as described by (ISO 14040, 2006)

The first step of an LCA involves defining the **goal and scope**. This phase describes the purpose of the study and the intended applications of its results. The goal is the contextual aspect of the LCA study that consists of determining the reasons for the specific research, the audience, and the subject of analysis. The scope, however, concerns modelling aspects of the LCA study and consists of the choice of the functional unit (FU), system boundaries, and environmental impact indicators. The FU reflects the function of the product or service being assessed. The system boundary defines which activities should be included within the LCA. The selection of the system boundary should be aligned with the goal of the study (ISO 14040, 2006). The **inventory analysis** step includes the construction of a model represented by a flowchart, in line with specifications provided in the goal and scope (Baumann and Tillman, 2004). This step includes all input and output materials used and emitted during the process. The third step is the **impact assessment**, which is the result of an environmental load "translation" from the inventory results into environmental impacts (Baumann & Tillman, 2004). The results of these steps are typically classified into numerous parameters and further reduced into environmental impact categories. According to ISO 14040 (2006), the **interpretation** step is the phase in which the total results obtained from the inventory analysis and impact assessment are combined and discussed in accordance with the defined goal and scope to form the basis for conclusions, recommendations, and decision-making (ISO 14040, 2006).

2.8 Prospective method in LCA

The assessment of emerging systems in LCA requires a future-oriented approach, such as prospective LCA. Prospective LCA is the study of a technology in its early stage of development, modelling it in the future as a more developed phase (Arvidsson et al., 2018). According to Pesonen et al. (2000), examining different scenarios of the same system and aiming to be aware of the changes due to both process development and market development of the technology system are ways to assess the future life cycle environmental impact of a system. One approach used to assess emerging technologies and support prospective LCA is break-even analysis. Wickerts et al. (2021) used this for assessing the climate change impact of a conversion device, requiring a certain efficiency improvement to break even with a current model. The environmental break-even point is the point where the development of the innovative device or system starts to present environmental benefits. Piccinno et al. (2016) described an additional example to predict the environmental impacts of certain chemical production processes at an industrial scale production based on the early laboratory research stage by identifying and simplifying the most important calculations for the energy use of the reaction step and for certain purification and isolation steps. According to Clancy et al. (2010), analysts should think creatively about existing data that can be used to show the environmental impacts early on in the development process. Presenting LCA results helps the development team to understand how significant various flows of process energy, raw materials, or another potentially important parameter can be for new processes. If visualised for the development team in an "actionable" way, this can provide important guidance even at the very early development stages, and stimulate the creativity of the development team (Clancy et al., 2010). Hermansson et al. (2022) assessed the future potential environmental impacts using a future-oriented LCA approach based on scenarios. More specifically, based on different variations in the life cycle inventory corresponding to the different development routes, sub-scenarios were created (Hermansson et al., 2022). The interrelationship between these sub-scenarios were assessed, and those most strongly connected were combined into future scenarios and assessed further (Hermansson et al., 2022). In this way, new systems were explored and compared to base case systems representing today's available technologies (Hermansson et al., 2022).

The environmental assessment performed and described in this thesis primarily consists of the meta-analysis of characterised life cycle impact assessment (LCIA) results. By normalizing data from different sources to the same FU to identify potential hotspots and compare a new conceptual system with a conventional existing system, this type of meta-analysis also supports a future-oriented assessment at early stages of development.

3 AIMS AND RESEARCH QUESTIONS

The overall aim of this study was to contribute to both the technical development and the methodological development of the sustainability assessment of an innovative system. The methodological development is focused on novel approaches for assessing the impacts of the system at early development stages. The technical development is targeted in the way that the assessment attempts aim primarily at providing input to the development of emerging technologies. This study will therefore provide guidance on how to explore the sustainability challenges and opportunities associated with technologies at early stages of development, with regard to the specific context of DWWT, P-rich products recovery, and recovered fertilisers use. To achieve this aim, two specific research areas (RA1 and RA2) were identified under which research questions were formulated. Figure 3 summarises how different research questions and appended papers relate to the different research areas.

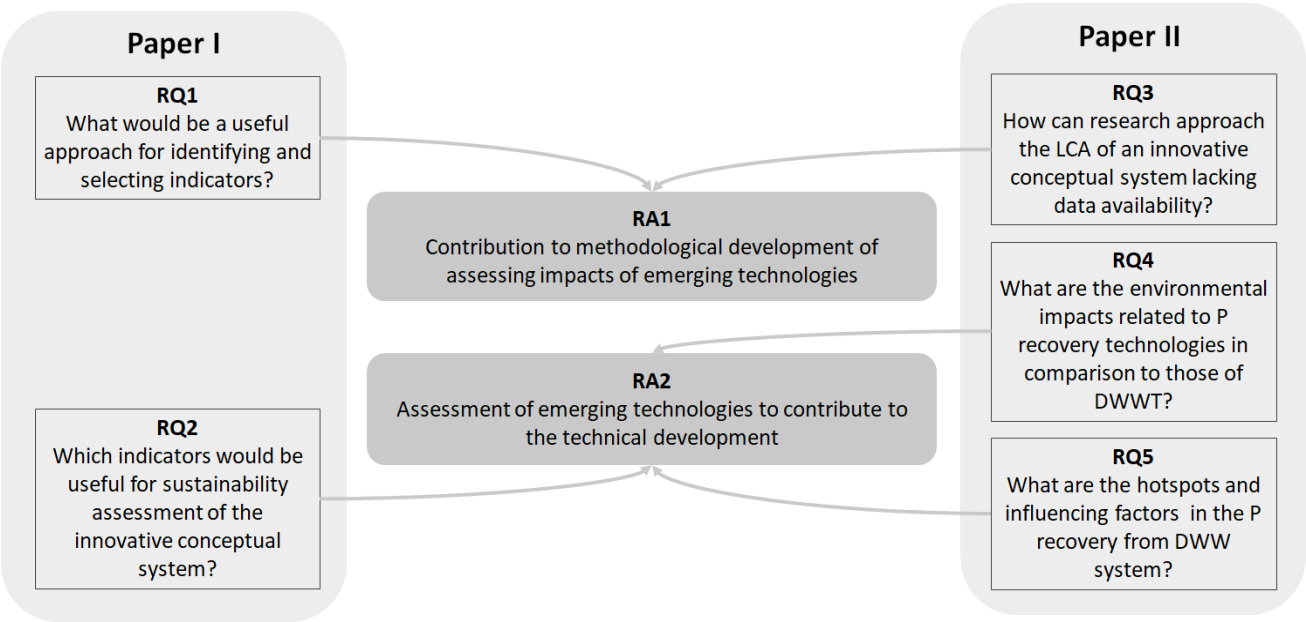


Figure 3 Schematic picture displaying the research questions (RQs), and how each of the appended papers are connected to the two different research areas (RA) in this thesis.

4 METHODOLOGY

The research presented in this thesis explores and contributes to the sustainability assessment and communication within the field of an innovative conceptual system that focuses on the recovery of P-rich products from DWW for producing and using new fertilisers.

This chapter is divided into four sections. Section 4.1 describes the overall methodology. In Section 4.2, the research method is explained: the information collected from interviews, questionnaires and literature reviews are used to design and develop a framework, and to highlight the actors' main concerns. Section 4.3 describes how sustainability indicators are identified and selected. The environmental impact assessment is explained in Section 4.4.

4.1 Overall methodological approach

The overall methodological approach of the research work of this thesis is represented in Figure 4.

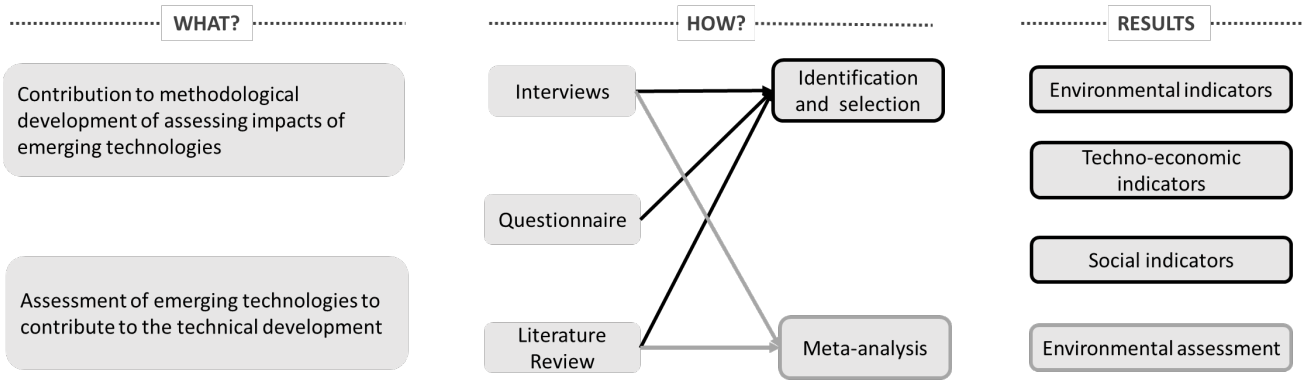


Figure 4 Workflow of the research described in this thesis. This figure represents the aim of the research and how the research could achieve its aim by obtaining the listed expected results: sustainability indicators (represented by the black boundaries) and the environmental impacts (represented by the grey boundaries)

What?

This research provides a scientific contribution to the methodological development of assessing the impacts of the emerging system. Specifically, it provides methodological contributions to both the selection of sustainability indicators and to how to generate an understanding of life cycle environmental impacts of an innovative conceptual system.

How?

The research work was supported by three research tools: interviews, questionnaire, and literature review. The information collected by using these tools was used to identify and select a list of

sustainability indicators (black boundary) and to perform a meta-analysis focused on life cycle environmental impacts (grey boundary).

Results

The environmental assessment results support the technical development, presenting information about the effects on the environment if the recovery of P is combined with the treatment of DWW. The list of environmental, techno-economic, and social indicators may in itself guide relevant actors with regard to important sustainability concerns. The list of indicators as well as the environmental assessment results are both results of innovative methodological approaches that contribute to the development of new methods for sustainability assessment.

4.2 Research methods

This section briefly explains and summarises the main data collection methods used in the context of this thesis. Further information is provided in the description of different parts of the research later in the thesis.

4.2.1 Interviews and framework development

The interviews aimed to provide information about the innovative technologies that constitute the system. This information includes material flow data, actors, and EU policies and contributes to the development of a conceptual system description as well as to sustainability indicator identification and development of a framework used in indicator selection. The framework highlights elements of the system and maps correlations between elements.

Researchers working on the technical development of the new system and scientists at the JRC, which is the EU's central scientific research institute, were interviewed.

The first group of researchers was interviewed to understand the type of technologies being used in each part of the system and the material flows that are associated with the operation of each process, i.e., the input and output material flows of each considered system. The second group, the JRC scientists, was interviewed to provide, based on the technical description of the processes, relevant actors and EU policies. Relevant actors are those who can affect the new system and learn their needs in relation to single processes of the system by being involved in the development process (Freeman, 2010; Lyon et al., 2020). EU policies that may influence the development of the system by having a direct impact on the EU decision-making in every member state cover issues like agricultural policy, food safety, and environmental standards.

4.2.2 Questionnaire

The questionnaire is a form developed to gather information about actor priorities with regard to various aspects of sustainability in relation to the considered system. To avoid overwhelming actors with a large number of indicators or too much detail, broader areas of concern were listed rather than single indicators. For this purpose, indicators were grouped and rephrased to make a limited and feasible list of "areas of concern" for the questionnaire (see supplementary material (SM) 1 Section 2 of Paper I for areas included in the questionnaire). The approached actors evaluated each area of concern. The environmental and the techno-economic indicators were graded from "not important" to "very important" on a six-grade scale, while the social indicators were ranked from one (least important) to seven (most important).

4.2.3 Literature review

Different documents were selected and reviewed for various parts of the research to collect information to contribute to both methodological development and sustainability assessment. The table below shows the types of documents selected for the literature review for various parts of the research.

Reviews generally involved generating a thorough summary and evaluation of available information in literature. The reviewed articles were selected based on the inclusion or exclusion criteria. Inclusion criteria is everything a study must have to be included, and exclusion criteria are the factors that would make a study ineligible to be included. Additionally, based on the reference lists of the articles, further relevant technical reports were found. The literature review approach for Paper I collates different studies that help to answer different questions related to identification and selection of sustainability indicators. The review approach for Paper II aimed towards filling a gap in research, by combining data from multiple independent studies.

Table 1 The table lists the type of documents reviewed in different stages of this research.

Selected documents	Paper I	Paper II
LCAs on DWW	✓	✓
LCAs on dairy industry	✓	✓
LCAs on P recovery	✓	✓
Reviews of LCAs on fertiliser use	✓	
Technical studies on DWW		✓
Technical studies on P recovery technologies		✓
Techno-economic assessments on innovative technologies	✓	
Studies on indicator selection criteria	✓	
Reports on social impact assessment	✓	
EU guidelines	✓	

Reviewed LCA studies focused on the dairy industry, DWW, and P recovery technologies and provided part of the information for both identifying environmental indicators and conducting the meta-analysis. The meta-analysis also required information collected from technical studies, which provide data about the P recovery potential of different technologies. Based on the information found in the LCA review study about fertiliser use, the environmental indicators list was extended.

Notably, the meta-analysis is focused on only two processes of the system, the DWWT, including the sludge treatment, and the P recovery process. Fertiliser use is not part of the meta-analysis. It is therefore recommended to perform a similar LCA review study about fertilisers use to establish the environmental indicators that are particularly useful for this part of the system.

The sustainability indicator list was further extended based on the information collected from the reviewed techno-economic assessment studies considering innovative technologies (not only limited to the specific system under study) and from reports on social indicators from EU and United Nations (UN). Furthermore, to select the indicators which best describe the performance in a sustainability assessment of the specific considered system, a set of indicator selection criteria was compiled on the basis of the information reported in different articles. This review was done to synthesize a set of indicator selection criteria for the specific context.

4.3 Sustainability indicators

4.3.1 Identification of sustainability indicators

Specific documents were consulted for identifying an initial list of sustainability indicators. Table 2 lists the sources considered: previous compilations in journal papers, technical reports, and European guidelines.

Table 2 List of documents reviewed for indicators for sustainability assessment.

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)

The environmental indicators were identified based on findings and further information in sources listed in two LCA review studies: Behjat et al. (2022), and Skowrońska and Filipek (2014). For the

techno-economic indicators, literature focusing on the assessment of innovative technologies was explored: Ögmundarson et al. (2020) combines indicators from LCA and techno-economic assessment for early stages of technology development; Labib et al. (2013) is an example of techno-economic assessment of a technology under development based on producing products from alternative material sources. Considering social indicators, reports that propose the practical and harmonized method of the initial UNEP SETAC Guidelines for Social Life Cycle Assessment of Products were consulted.

4.3.2 Selection of sustainability indicators

The contribution to the methodological approach for the selection of sustainability indicators relevant for the assessment of this innovative conceptual system is described in this section. A practical subset of the long list of indicators identified by reviewing different scientific documents, were selected using three screening processes.

The first screening process consisted of comparing the indicators found in the literature with the elements that constitute the developed screening framework. Next, the list of indicators obtained from the first screening was filtered based on the actors' interests collected through the results of the questionnaire. Finally, a further screening was applied based on the indicator selection criteria proposed in literature. A representation of this screening process is shown in Figure 5.

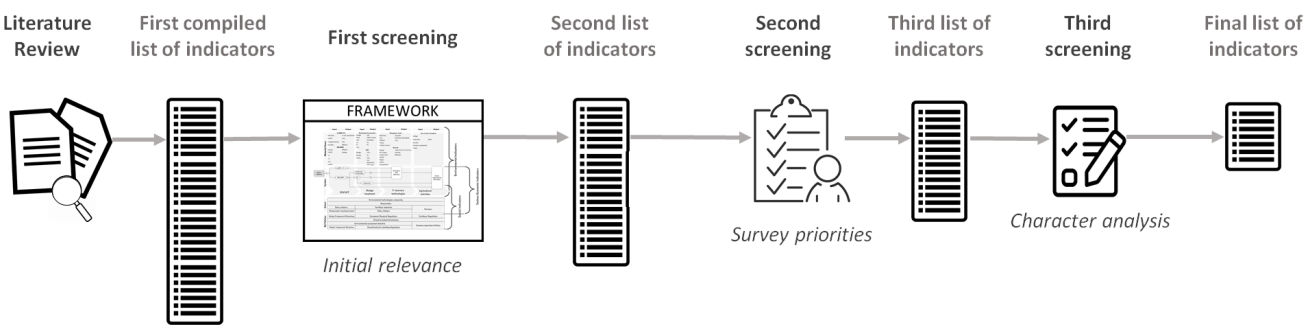


Figure 5 Representation of the approach to select the sustainability indicators.

After the screening process, a final refinement and polishing step would ensure that the selected indicators are completely adapted to the context. The selected environmental and techno-economic indicators' units need to be attributed to a specific FU. Moreover, some of the techno-economic and social indicators need to be reworded to be more focused and adaptable for the assessment of the considered system.

First Screening

By using the developed screening framework, a set of indicators was selected during the first screening. The input and output material flows listed in the generated framework were compared and assigned to the environmental indicators in the compiled initial list of indicators guided by ReCiPe 2016 LCIA (Huijbregts et al., 2016). This provided clear advice on which indicators are connected to each material flow (Section 3 of the SM1 of Paper I presents an overview of the LCIA methodology). Only the environmental indicators with a matching input or output material in the framework were retained.

Techno-economic and social indicators were already sorted into *subcategories* in the reviewed literature. The social indicators, based on the structure in the UNEP-SETAC guidelines, were also already categorised into *stakeholder* groups (UNEP, 2021). Both techno-economic and social indicators that can support relevant actors by warning them about the possible consequences that they may face as the result of operating the specific system, and thereby enabling them to make decisions, were selected. Moreover, social indicators that supported decision-making with regard to relevant EU policies were selected.

Second Screening

On the occasion of the ESPC4[1] conference and PERM5[2] meeting in June 2022 in Vienna, Austria, different areas of concern were prioritised by different actors through the questionnaire described in Section 4.2.2. Their priorities were used to select indicators in areas of high concern and remove others. The first three or four areas of concerns that were considered of higher importance were considered to select indicators in each indicator group: environmental, techno-economic and social.

Third Screening

Lastly, the list of indicators was further screened based on the selection criteria. General selection criteria were used to reduce the number of indicators from a large set of potential ones (Lebacq et al., 2013). A set of reviewed studies proposed and used selection criteria for choosing sustainability indicators. The compiled selection criteria used in the screening process are listed in Table 3 (Section 3.3.3 in Paper I describes how these selection criteria were identified and selected for this screening

[1] The European Sustainable Phosphorus Conferences bring together companies, stakeholders, regional and national authorities and researchers to discuss phosphorus and nutrients sustainability actions and policies.

[2] This meeting linked science, industry, agriculture, and policy-makers in addressing how to improve uptake of project recommendations by policy-makers and users through market and identified perspectives for research and policy and implementation gaps.

process). For each selection criterion, one or more questions were formulated to guide the selection process for the sustainability indicators. Indicators that did not correspond to these selection criteria were removed.

Table 3 List of sustainability indicator selection criteria used for the second screening. For each selected criterion, a few questions were elaborated and used in indicator selection (see table 2 in Paper I for how they appear in different sets in literature and what their meaning is).

Criteria	Questions
Practicability	▪ Are there enough information and data to allow the use of this indicator? ▪ Are timely data available for this indicator?
Quality	▪ To use this indicator, is there sufficient information based on accurate and robust data?
EU Policy Responsiveness	▪ Is this indicator responsive to EU policies?
Geographical scope	▪ Does this indicator provide a sufficient level of cross-European country comparability? ▪ Does the scope of the indicator match the geography in question?
Guiding	▪ Does this indicator provide information about how to move forward with future actions for sustainability improvement?
Adaptability	▪ Is the indicator adaptable and applicable to a range of systems of different sizes and types? ▪ Is the indicator universal enough for comparison across regions?
Participatory	▪ Is the indicator accessible to different users? Is the indicator "comprehensible?"
Representativeness	▪ Is the indicator close to the context which it intends to indicate? ▪ Does this indicator provide information about how the new systems will impact the environmental, economic, and social spheres?

4.4 Environmental impact assessment

A common method for assessing the environmental impacts of a system is LCA. LCAs have been used to assess the environmental impacts associated with dairy production and P recovery from different wastewaters, but no LCA study that combines these two technical systems has yet been reported. Furthermore, it was still too early to create an original LCA using data from the REFLOW ETN project. Therefore, information from previous studies was extracted and compared to identify potential environmental challenges and opportunities and thereby provide knowledge and guidance during early stages of the development of these technologies.

In order to compare results from LCA studies of dairy products with results from LCA studies of P recovery technologies made for other contexts, an innovative approach, similar to that suggested by Hermansson et al. (2019), called meta-analysis was employed. The meta-analysis extracted and recalculated literature results owing to the lack of published LCAs on P recovery from DWWTs. Moreover, further documents describing P recovery technologies and the chemical characteristics of DWW were employed to enable the integration of LCA results for the new combined system of P recovery in the context of DWWT.

4.4.1 Meta-analysis

The meta-analysis of the studies collected from the literature review is described in this section. This meta-analysis contributes to the development of the technologies with regard to the understanding of environmental impacts.

When extracting environmental impact results from published LCA studies, it must be noted that the results are not directly comparable due to differences in FUs, environmental impact categories, system boundaries, and type of inventory data used. Therefore, the specifics of each included study must be carefully considered.

The system intended to be assessed was a combined system of DWWT and P recovery and details were defined based on the information collected by interviewing the researchers working on the technology development. Figure 6 shows the combined system and the parts that I wanted to extract information from.

Collecting data

Impacts related to DWWT (gate-to-gate in the upper part of Figure 6) and P recovery processes as such (gate-to-gate in the lower part of Figure 6) were required. Hence, data from different studies were extracted and restructured.

Recalculating data

The information on environmental impacts was rescaled to the same FU. As the present study intended to find the impacts related to DWWT, in the first step, impacts related to 1 L of processed milk were assessed (see the upper system in Figure 6). For the second step, however, 1 kg of P recovered was a common FU (see the lower part of Figure 6), as also strongly recommended in the literature on LCA of P recovery technologies. Together with the fact that this study is intended to be used in the development of P recovery technologies in a dairy context, 1 kg of P recovered was therefore used as a FU in the final compilation.

In the second step, when impacts of the DWWT, as gathered from the dairy LCAs, was recalculated to relate to the P in the DWW, further information was needed. Therefore, DWW volumes data (scaled to 1 L of processed milk, collected from the LCAs in the dairy industry; see Table 13 in the SM of Paper II) and the typical P concentration data of DWW (from seven studies on DWW characteristics; see Table 14 in the SM of Paper II) were collected and analysed. The average value of P concentration calculated was 67 mg/L. The average was used as the intention was no to scale for a specific situation but rather for an average overall situation.

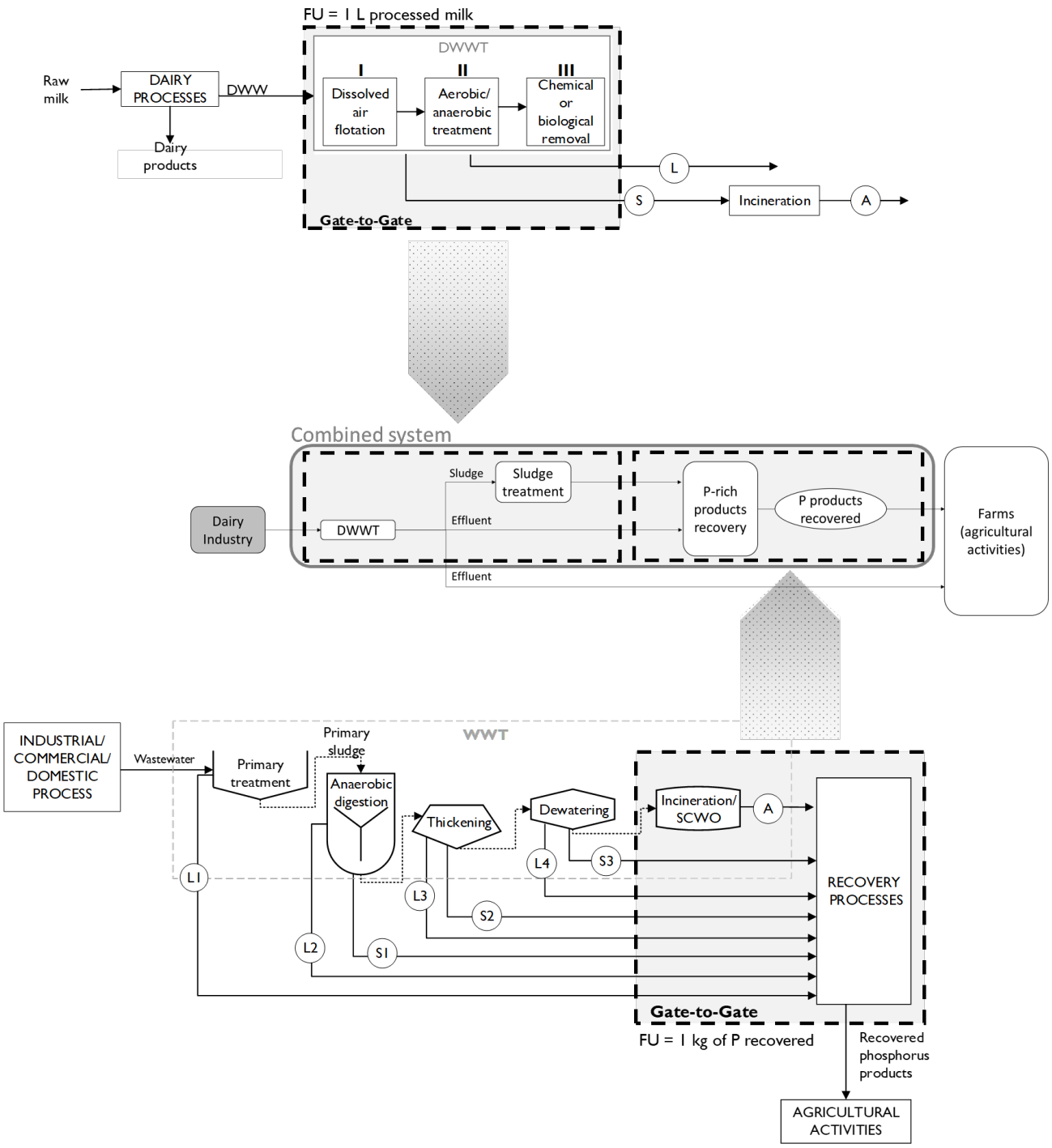


Figure 6 System boundaries for the reviewed studies and for the system parts that were extracted for comparison in the present study are marked with bold dashed boxes for the dairy wastewater treatment (DWWT) (upper system) and the P recovery process (lower system). Middle system shows the combined conceptual system considered in this thesis. DWW=dairy wastewater; FU=functional unit; WWT=wastewater treatment. The letters represent liquid flow (L), sludge (S), and ash (A) obtained from different processes of the WWT and used in the recovery processes; the numbers added in the lower system show the different extraction points considered in the reviewed studies and refer to Table 2 of Paper II.

Assembling data

Finally, to relate the extracted and rescaled environmental impact results of the DWWT process to those of the P recovery process in a conceptual combined system (as represented in Figure 6, the middle system), the collected and analysed data on the efficiency of different P recovery technologies (from the overview by Egle et al. (2015)) were used.

By setting the concentration of P in the DWW to an average number, the P flow in the DWW for the dairy LCA studies could be calculated, and establishing the P recovery potential for different types of technologies made it possible to calculate the typical DWW volume needed for the recovery of 1 kg of P (see SM of PAPER II Section 4 for further details about the calculations). Finally, it was possible to relate the environmental impact of the DWWT to that of P recovery for the same flow of P.

When evaluating the available information in the reviewed LCA studies, it was observed that only a few environmental impact categories were common to several studies and could be used in the final comparative work: cumulative energy demand (CED), climate impact based on global warming potential (GWP), and acidification based on acidification potential (AP). It would have been interesting to investigate more categories, but these were the only ones that the available material allowed for.

5 RESULTS AND DISCUSSION

5.1 RQ1: What would be a useful approach for identifying and selecting indicators?

5.1.1 First compiled list of indicators

By reviewing documents as explained in Section 4.3.1, an initial list of 382 indicators was compiled (SM2 of Paper I). By removing duplicates, the list was narrowed down to 230 indicators (SM2 of Paper I). Through the three screening steps, based on the use of the developed framework, the questionnaire results and the selection criteria, this large set of indicators was further refined.

It should be noted that the environmental indicators included in the set of 230 indicators were specific for the assessment of a system focused on dairy industries, wastewater treatment, P recovery technologies, or fertiliser use. The techno-economic and social indicators, however, could be used for the sustainability assessment of systems, whether innovative or not, that involve other technologies, than those mentioned above.

5.1.2 Developed framework

All the information collected through the interviews with experts supported the development of the screening framework (Figure 7). The framework lists material flow data, actors, and EU policies as well as their connection to the different parts of the conceptual system and was used to select sustainability indicators in the first screening process.

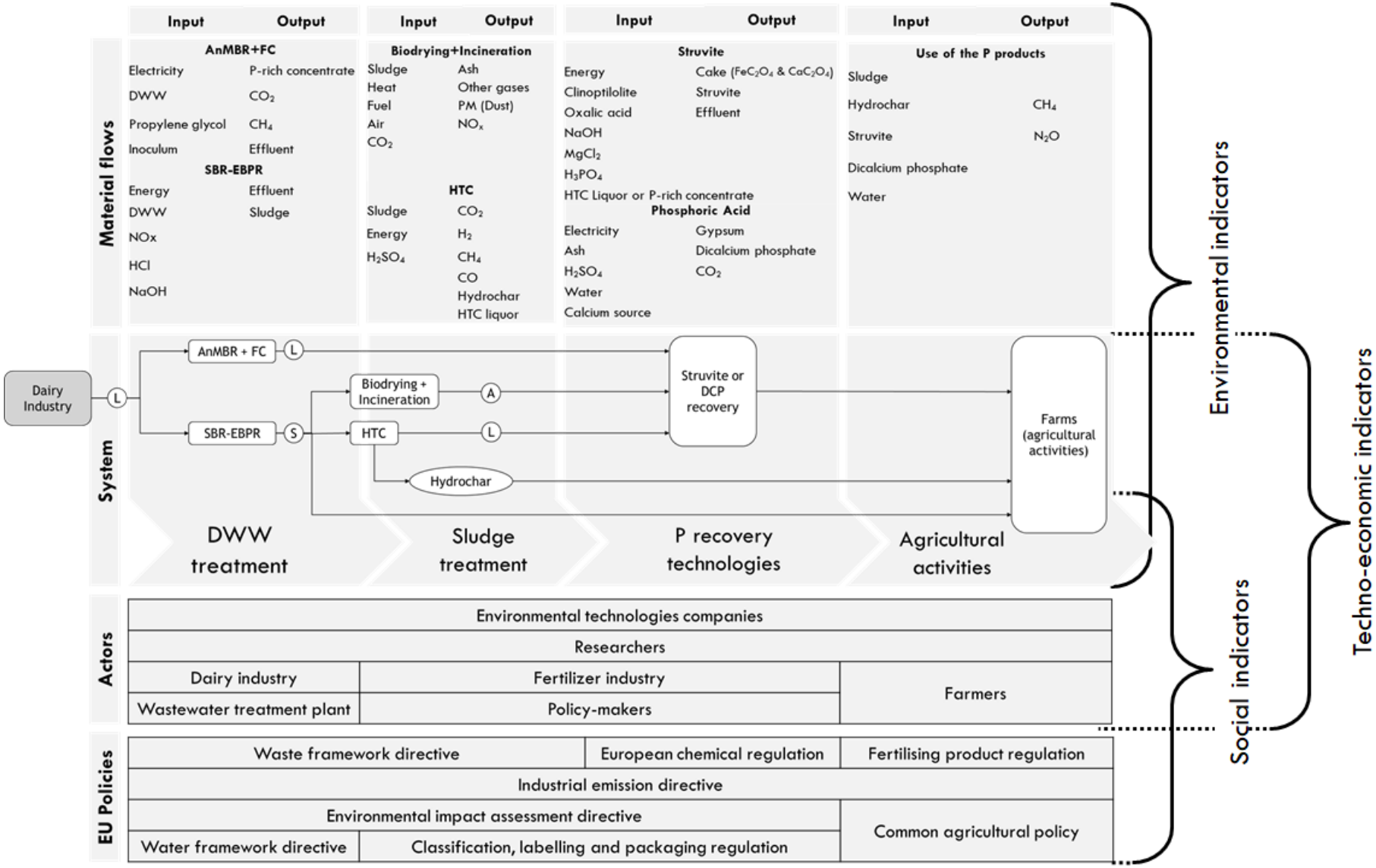


Figure 7 The screening framework, representing the structure of how the stakeholders and the EU policies are linked to the technical aspect of the considered system, used to evaluate environmental, techno-economic and social indicators.

5.1.3 Actors' priorities

During the conference (see Section 4.3.2 *Second screening*), 18 actors participated and responded to the survey (please see SM1 Section 6 of Paper I for their general affiliations). Figure 8 presents the actors' priorities in terms of areas of concern for assessing sustainability indicators.

Within the environmental area, there was a great interest amongst the responding actors for assessing *ecotoxicity, climate change*, *eutrophication,* and *energy use*. Less interest was observed toward *acidification*, *land use*, and *water use*. With regard to techno-economic aspects, from the participating actors' perspective, the *rate of return* or rather the gains or loss of an investment over a period of time, the *existing market*, which is the amount of ongoing trade of output, and the *risk* due to a variation of the return, were the most relevant areas of concern. Regarding the social aspects, there was significant interest based on the responding actors' expertise for the a*ssessment of consumer health, safety, and satisfaction of final products,* and the *capacity to engage local actors for market development* (see Figure 8).

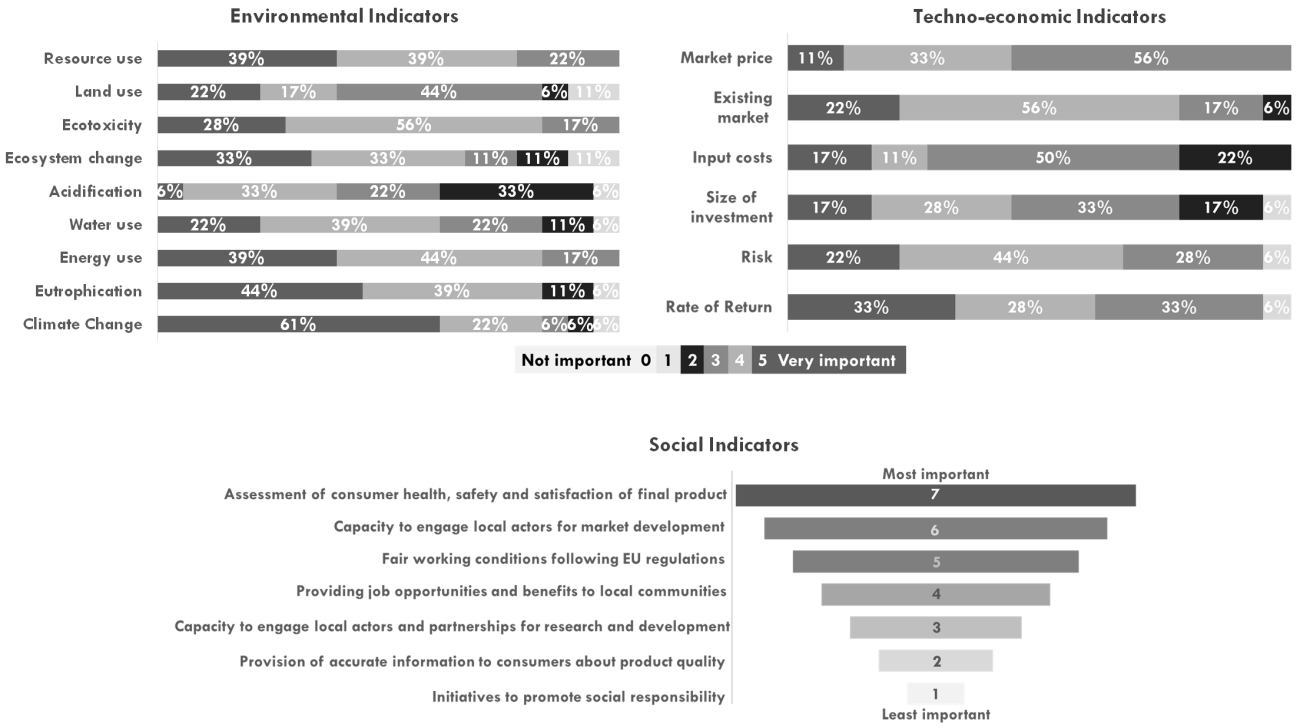


Figure 8 Response to actor questionnaire ranking the importance of different environmental, techno-economic, and social aspects. The environmental and techno-economic indicators are graded from "very important" to "not important", while the social indicators are ranked from seven (most important) to one (least important).

5.1.4 Indicators Selection

By screening the list of indicators using the three steps of the process, a final list of 26 indicators was compiled. Table 4 presents an overview of the number of indicators suggested in the literature and selected through the screening processes for each category of indicator.

Table 4 Number of indicators after removing duplicates and after each step of the screening approach.

Indicators	Literature review	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

Environmental indicators

From the detailed analysis of each single process in the technical system, 13 environmental indicators were selected from the first screening. These were the indicators allocated to each environmental impact due to the technologies of each process and their connected material flows. The indicators, selected through the second screening, were those classified under the areas of concern of *climate change*, *eutrophication potential*, *energy use*, and *resource use*. In total, 7 of 13 environmental indicators were selected during the second screening. Notably, based on the questionnaire's results, ecotoxicity was an area of concern that should be considered. However, based on the results of the LCIA analysis applied within the first screening, ecotoxicity was not found to be a significant environmental impact, and not included in the final list, except with regard to particulate matter. All the environmental indicators selected by the second screening were retained after the third screening. The data needed to assess the environmental impact by using these indicators were considered available and easy to collect and therefore responded to the criteria of *practicability* and *quality*. Furthermore, these indicators could check whether the system was in line with the EU policies (see Section 4.3 in the SM1 of Paper I for the considered EU policies); therefore, these indicators were also *EU policy responsive*. The results obtained using these indicators were important to *guide* further actions in the system development in future.

Techno-economic indicators

Based on the information reported in the framework, 19 techno-economic indicators were selected. These were the indicators that were linked to the actors of each process listed in the framework. Based on the information collected from the questionnaire and the selection criteria, the list of indicators was narrowed down to 11 and then seven, during the second and the third screening, respectively. These

final seven indicators were mainly selected because, apart from meeting most of the eight common criteria, they were the most easily described with physical units. These indicators met the criteria of *practicability, guiding,* and *adaptable and representative*. Furthermore, these indicators were also accessible to different users, easily understood, and easy to use for decision making; hence, they met the criterion of being *participatory*.

Social indicators

Based on the information reported in the framework and that collected from the questionnaire, 70 and 42 social indicators were selected from the first and second screenings, respectively. Throughout the third screening, based on indicator selection criteria, the list was narrowed down to 12 indicators. The main criteria that these indicators met are *guiding*, *EU policy responsive*, and *participatory*.

5.2 RQ2: Which indicators would be useful for sustainability assessment of the innovative conceptual system?

Table 5 reports the final list of sustainability indicators selected, and the unit of measurement and subcategories when applicable. The unit considered here for calculating the environmental and the techno-economic impacts is the mass of the final recovered product, as it is the most common and also recommended FU to be considered for similar systems. Reviewed LCAs studies proposed 1 kg of the P-rich product recovered as the appropriate FU (see further details in Paper II).

One of the limitations of the use of the selected indicators is that they can be used differently depending on the background system, e.g. the geographic area considered (Baumann et al., 2013). Although this set of indicators met the selection criterion of *geographical scope*, it did not imply that it was equally applicable to all European countries. The EU policies listed in the framework and used in the first screening are various regulations and directives. The regulations are legal acts that apply automatically and uniformly to all EU countries and are binding for all EU countries, without needing to be transposed into national law. On the contrary, directives must be incorporated by EU countries into their national legislation. These directives require EU countries to adopt measures to incorporate them into national law, based on local circumstances, in order to achieve the objectives set by the directive (European Commission, 2022). It is important to have sufficient information to allow the application of these indicators in different countries in Europe.

Table 5 List of sustainability indicators selected for the assessment of the considered system. The units of measurement are here considered to be attributed to the final defined mass (FU) of the recovered products. The unit for the environmental indicators is adopted from different life cycle impact assessment (LCIA) methodologies. The techno-economic and social indicators are classified into different subtopics, and stakeholders. Some indicators have been slightly modified to focus on the assessment of the considered system (see words in bold and with strike-through).

	Stakeholders	Subcategories	Indicators [Area of interest]	Unit	LCIA methodologies
Environmental			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 $PM_{2.5}$	ReCiPe 2016 v1.1
			Fossil depletion	kg oil eq	ReCiPe 2016 v1.1
			Mineral depletion	kg Sb eq	CML 2002
Techno-economic		Financial	Annual operating labour costs	€/year	
			Total production	€/year	
			Gross profit	profit/year	
			Simple Rate of Return Investment	%	
		Techno-economic cost	Payback time	time	
		Business indicators	~~Industrial~~ **REFLOW system** producer prices	**€**	
			~~Industrial~~ **REFLOW products** production	**mass/month**	
Social	**Workers**	Smallholders including farmers	Participation ~~in~~ **of** farmers' organization **in the design process** [Inclusiveness]		
			~~Evidence~~ **Estimation** of crop yield [Productivity]		
			~~Evidence~~ **Estimation of the evidence** of 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 ~~with the organization~~ **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 ~~organization~~ **of system** ~~obtained~~ 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		

Interestingly, among all these indicators, there were no indicators that specifically considered local authorization aspects or the expected public acceptance of installation of the technologies, although these aspects can be expected to be relevant for this assessment. This indicated that the coverage of selected sources for the identification of indicators was not broad enough. In other work that was not included in the indicator identification process, such indicators were included to cover the vulnerability to public acceptance and to the authorization process required for the installation or operation of the system (Bertanza et al., 2015)

5.3 RQ3: How can research approach the LCA of an innovative conceptual system lacking data availability?

Paper II demonstrates an approach for dealing with the non-availability of life cycle inventory data for the system under study, which is by critically editing disaggregated LCIA results from described LCAs of related systems.

Through the interviews with the researchers working on the technical development, it was established that the innovative technologies were focused on: (i) accumulation and crystallisation or mineralisation of P-rich products (struvite or phosphoric acid) from liquid effluents; (ii) drying or hydrothermal carbonisation of sludge; and (iii) extraction of heavy metal-free, water-soluble phosphate salts, and phosphoric acid from ash from sludge incineration, allowing for the production of new fertilisers and enabling more circular P flows through society in all cases.

Based on this information, only a few studies (shown in Figure 9) have reported sufficiently disaggregated data for the same type of technologies as described by the technical researchers.

From the literature screening, nine studies that dealt with LCA of dairy industries, and six that considered LCA of P recovery technologies allowed for the extraction of environmental impact data for the DWWT and recovery process explicitly. Furthermore, one paper with an overview and description of technologies for recovering P and seven on the chemical characteristics of dairy industry wastewater (see Figure 9) were consulted for integrating the two sets of studies to understand the impacts of the combined system.

A brief technical description of the P recovery technologies considered in the selected LCA studies are presented in Table 2 of Paper II.

The environmental impacts of the P recovery technologies, in municipal WWT contexts, which are different from the dairy contexts focused on in this study, were compared with those of DWWT. This comparison could establish if there would be large environmental challenges related to adding P

recovery to existing DWWTs, and it established the information that needs to be considered in the development and implementation process.

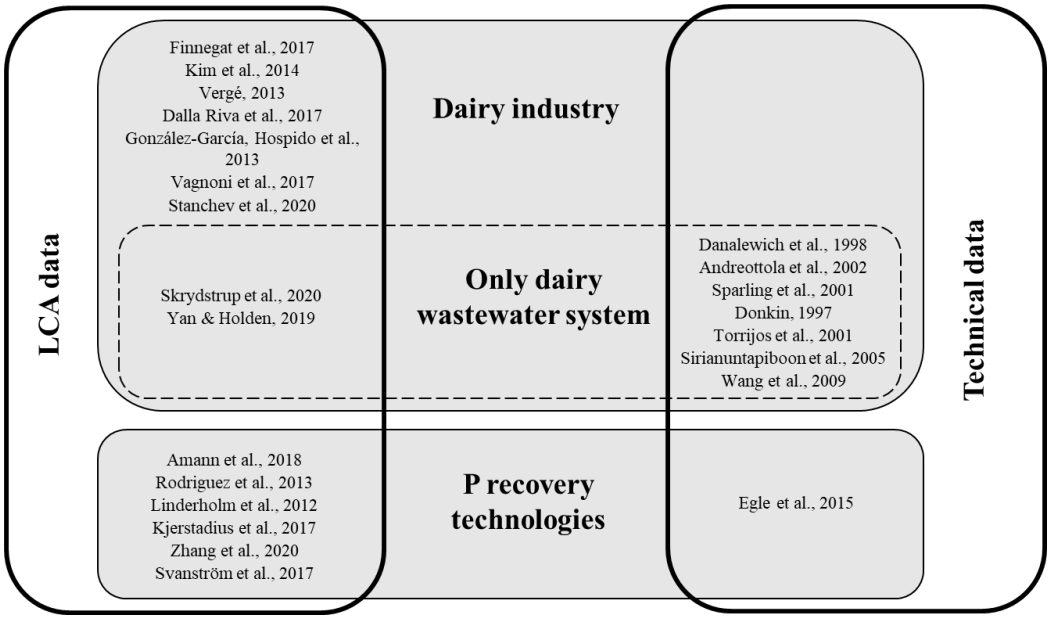
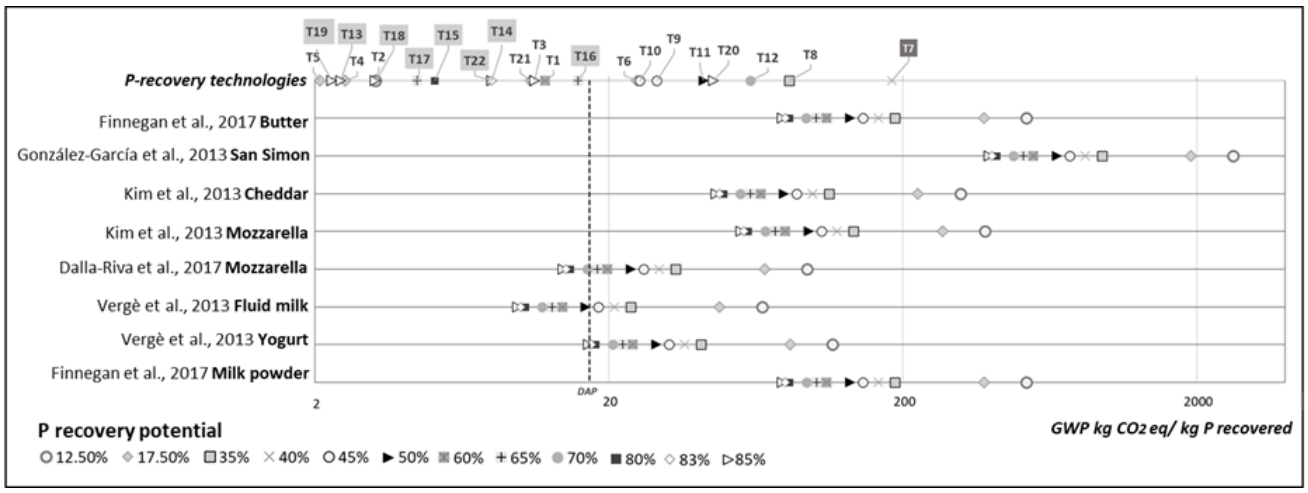


Figure 9 Diagram illustrating the number and type of articles ultimately selected and reviewed for the meta-analysis. Reprinted from "A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater" by M Behjat, M. Svanström, G. Peters, 2022, *Journal of Cleaner Production* 369, 133307.

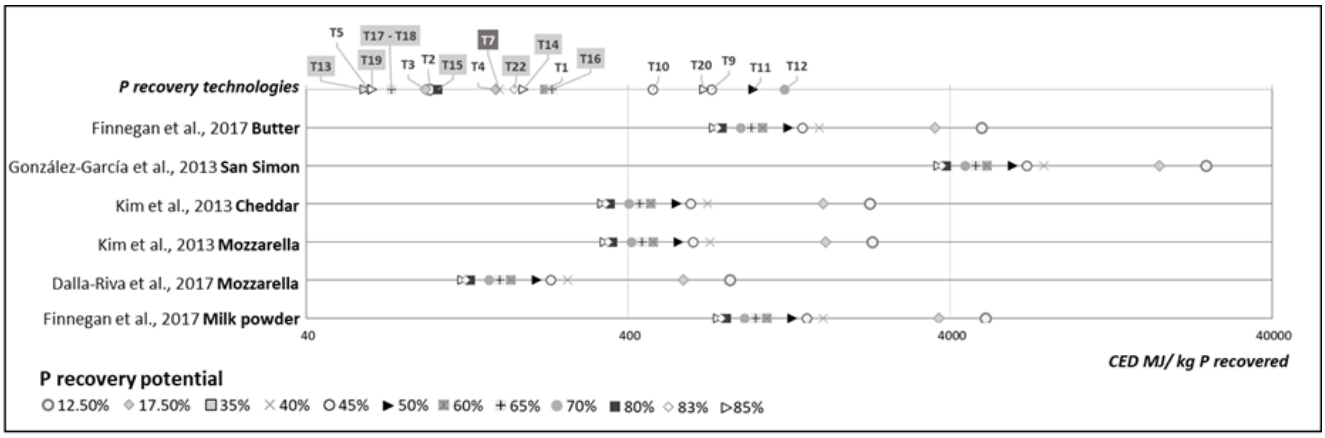
5.4 RQ4: What are the environmental impacts related to P recovery technologies in comparison to those of DWWT?

The environmental impacts of the studied kinds of P recovery technologies are compared to those of DWWT (see Figure 10). Figure 10 shows the environmental impacts due to the recovery of 1 kg of P (top line in each chart) and compares them to those of DWWT (all other lines in each chart) for the three environmental impact categories that allowed for cross-comparisons between the two sets of LCA studies: CED, climate impact, and acidification. The same marker is used for all technologies with the same P recovery potential and may, therefore, appear more than once in the first line. The impact of an eventual P recovery process implemented in a dairy context can be estimated as the sum of two values: the value for the P recovery in the uppermost line and the value for the same marker in any of the other lines. However, it is likely that in a real case, either the DWWT or the P recovery needs to be modified in a combined process, leading to lower or higher impacts than this combination.



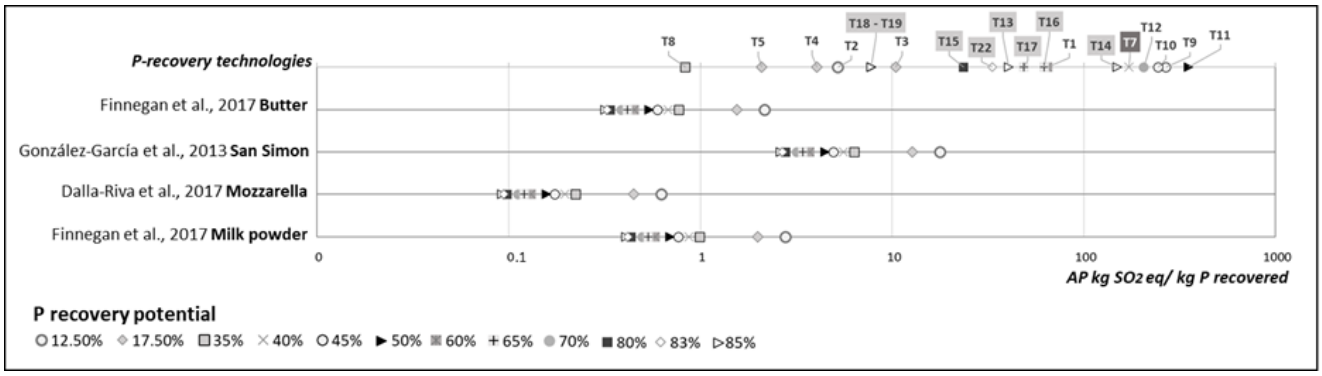
a)

Figure 10a Climate impact as global warming potential (GWP) for P recovery (top line for each chart) and for DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). The dark dashed line represents the climate impact per kg of P in DAP (Zhang et al., 2017). Note the logarithmic scale. Reprinted from "A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater" by M Behjat, M. Svanström, G. Peters, 2022, *Journal of Cleaner Production* 369, 133307.



b)

Figure 110b Energy use as cumulative energy demand (CED) for P recovery (top line for each chart) and DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). Note the logarithmic scale. Reprinted from "A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater" by M Behjat, M. Svanström, G. Peters, 2022, *Journal of Cleaner Production* 369, 133307.



c)

Figure 10c Acidification impacts as acidification potential (AP) for P recovery (top line for each chart) and DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). Note the logarithmic scale. Reprinted from "A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater" by M Behjat, M. Svanström, G. Peters, 2022, Journal of Cleaner Production 369, 133307.

5.5 RQ5: What are the hotspots and influencing factors?

According to the data calculated, it was observed that most technologies that recover P from ash have a lower impact because the incineration process was not included (T13–19 and T22). Conversely, it was found that technologies recovering P from ash (T20–21) have the highest impacts when incineration is included. The technology that includes anaerobic digestion (AD) and represents a larger system is surprisingly not among the highest (T7), but it is noteworthy that system expansions have been removed from these results to avoid consideration of any potential gains from gas or energy products from AD or incineration to allow for a focus on the technologies themselves.

Considering further details on hotspots and influencing factors, most of the technologies that recover P from the liquid phase (T1–8) have a low contribution to CED owing to a low demand of energy and input chemicals. For P recovery from sludge solids (T9–12), the CED is primarily due to energy and chemical demands. Considering the case of the acid wet chemical and wet oxidation process of T11, a higher CED is related to its demand for oxygen and electricity and disposal and treatment of the remaining solids and heavy metal slag.

Considering GWP, it was largely due to emissions related to the heat demanded by the ammonium stripper (T6) (Kjerstadius et al., 2017). For wet chemical leaching from sludge (T9 and T11), the greenhouse gas emissions were primarily related to the production of the chemicals used (citric acid, sodium hydroxide, and sulfuric acid) and the high demand for coke and natural gas used during sludge mineralisation (Amann et al., 2018). Technologies that recover P from ash require higher temperatures;

therefore, more energy is required for these processes, which ultimately influences the climate impacts (Linderholm et al., 2012).

However, no technologies involving incineration have reported the impact of AP. Factors that have been reported to influence acidification impacts are electricity use and NH_4 emissions in air during stripping and struvite or calcium phosphate formation, which therefore require careful pH adjustment (Rodriguez-Garcia et al., 2014).

6 CONCLUSIONS

This thesis generated methodological development and assessment contributions for the sustainability of an innovative conceptual system: P recovery for fertilisers use from DWW. The main challenges in assessing the sustainability of this system were: 1) the definition of a representable set of sustainability indicators and 2) the environmental assessment of an innovative system lacking data availability.

With this work I showed that a set of indicators can be identified and selected through tools that guide the selection of the most representative indicators for the sustainability assessment of this innovative conceptual system. The selection tools, based on the elements that constitute the system, the actors' interests, and the EU policies that may have an influence on the development of these kind of systems, enables the screening of an initial set of sustainability indicators to a practical final set.

I have also showed that the lack of data availability can be overcome by a meta-analysis by repurposing LCA results from the literature and recalculating them for a new context. The meta-analysis enables the identification of the environmental impacts and the hotspots in the early phase of technology development.

The results presented in this thesis, apart from the methodological contributions is a set of 26 sustainability indicators screened from an initial set of 382. Furthermore, according to the results presented in this study, installing P recovery as part of or after DWWT would normally not incur large additional environmental costs compared to the current DWWT with regard to climate impact or energy use; in general, the processes recovering from a liquid flow have a lower impact than when sludge is the P source. However, when sludge is incinerated and P is recovered from ash, the impact is typically higher.

These were the major findings of this study, which could contribute to the development of a method that is practical to implement and is time and resource efficient, which are valuable characteristics of sustainability assessment tools in the technical development process. Moreover, these findings contribute to extending knowledge of the life cycle environmental impacts that can be expected of P recovery in a dairy context and provide useful guidance for further technology development and environmental assessment.

7 FUTURE RESEARCH

Nutrient recovery from various waste streams is an area with many technical possibilities. There is a large amount of technical development going on related to resource recovery from waste streams, for fertilisers use, and guidance is needed in the technical development of these technologies. The findings in the present work will provide input to and guidance for future research aiming to contribute to the technical development of technologies related to the recovery of nutrients. Sustainability assessment of waste stream, wastewater or sludge management systems, or similar, is likely to face different challenges. The applicability of proposed methods outside of the exact contexts in which they were developed can be tested and further developed in various other case studies.

This research only partially contributes to establishing how, when, and under what conditions the recovery of nutrients from wastewater would lead to an environmental gain. Indeed, Paper II described in this thesis explores only the climate impact, energy use, and acidification of the P recovery technologies and DWWT, and without including the environmental effects due to the use and application of these recovered products in agricultural activities. More efforts can be put into adding other parts that were not included in the current thesis. Further, the information was compiled using a meta-analysis approach. This method has its merits for early stages of technology development, but the information should be updated once more data is available for the specific technologies in the context they are going to be applied. Further development of the technologies will lead to a deeper understanding of systems, leading in turn to a more detailed account of the environmental impacts and the respective environmental indicators presented in Paper I.

From the work in Paper I, sustainability indicators were identified and selected. These indicators are the primary elements needed for a future multicriteria analysis (MCA) of the system. The results of an MCA will contribute to the holistic understanding needed for the technical development of emerging systems as it includes all the three different sustainability dimensions: environmental, techno-economic, and social. This would be a fruitful area for further work.

8 REFERENCES

Arvidsson, R., Tillman, A.-M., Sandén, B., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA: Prospective LCA. Journal of Industrial Ecology 22, 1286-1294.

Ashekuzzaman, S.M., Forrestal, P., Richards, K., Fenton, O., 2019. Dairy industry derived wastewater treatment sludge: Generation, type and characterization of nutrients and metals for agricultural reuse. Journal of Cleaner Production 230, 1266-1275.

Baldassarri, C., Allacker, K., Reale, F., Castellani, V., Sala, S., 2017. Consumer Footprint. Basket of Product indicators on Housing. Joint Research Centre.

Baumann, H., Arvidsson, R., Tong, H., Wang, Y., 2013. Does the Production of an Airbag Injure more People than the Airbag Saves in Traffic? Journal of Industrial Ecology 17(4), 517-527.

Baumann, H., Tillman, A.M., 2004. The Hitch Hiker's Guide to LCA. Studentlitteratur AB, Lund.

Behjat, M., Svanström, M., Peters, G., 2022. A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater. Journal of Cleaner Production 369, 133307.

Bertanza, G., Canato, M., Laera, G., Tomei, M.C., 2015. Methodology for technical and economic assessment of advanced routes for sludge processing and disposal. Environmental Science and Pollution Research 22(10), 7190-7202.

Bradford-Hartke, Z., Lane, J., Lant, P., Leslie, G., 2015. Environmental benefits and burdens of phosphorus recovery from municipal wastewater. Environmental Science and Technology 49(14), 8611-8622.

Clancy, G., Fröling, M., Peters, G.M., Svanström, M., 2010. Environmental challenges when developing renewable materials to replace non-renewable materials - receiving guidance

from LCA studies, 9th International Conference on EcoBalance 2010 'Towards & Beyond 2020' Tokyo, Japan.

Collingridge, D., 1982. The social control of technology.

Demirel, B., Yenigun, O., Onay, T.T., 2005. Anaerobic treatment of dairy wastewaters: a review. Process Biochemistry 40(8), 2583-2595.

EASAC, 2016. Indicators for a circular economy. German National Academy of Sciences, Germany.

EDA, 2018. Economic report 2017/18. EDA (European Dairy Association).

EEA, 2000. Environmental indicators: Typology and overview.

EEA, 2004. EEA Glossary - Social indicator. http://europa.eu.int/comm/employment_social/news/2001/oct/i01_1395_en.html. (Accessed October 2022).

EEA, 2005. EEA core set of indicators - Guide. European Environment Agency, Luxemburg: Office for Official Publications of the European Communities.

Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. Resources, Conservation and Recycling 105, 325-346.

European Commission, 2009. Economic impact of the abolition of the milk quota regime. JRC, Seville.

European Commission, 2016. Circular economy: New Regulation to boost the use of organic and waste-based fertilisers (MEMO/16/826). Brussels.

European Commission, 2017. Study on the review of the list of Critical Raw Materials.

European Commission, 2020. COM/2020/474 final Critical Raw Material Resilience: Charting a Path towards greater Security and Sustainability.

European Commission, 2022. Types of EU law. https://ec.europa.eu/info/law/law-making-process/types-eu-law_en. (Accessed December 2022).

European Parliament, 2022. Circular economy: definition, importance and benefits. https://www.europarl.europa.eu/pdfs/news/expert/2015/12/story/20151201STO05603/20151201STO05603_en.pdf https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits#:~:text=The%20circular%20economy%20is%20a,reducing%20waste%20to%20a%20minimum. (Accessed October 2022).

EUROSTAT, 2009. Principal European Economic Indicators - A statistical guide. European Comission, Luxembourg: Office for Official Publications of the European Communities.

Filippelli, G.M., 2008. The global phosphorus cycle: Past, present, and future. Elements 4(2), 89-95.

Frederiksen, P., Kristensen, P., 2008. An indicator framework for analysing sustainability impacts of land use change. Sustainability Impact Assessment of Land Use Changes, 293-304.

Goedkoop, M., Indrane, D., de Beer, I., 2018. Handbook for Product Social Impact Assessment 2018.

Gudmundsson, H., 2003. The Policy Use of Environmental Indicators-Learning from Evaluation Research. The Journal of Transdisciplinary Environmental Studies 2.

Hermansson, F., Heimersson, S., Janssen, M., Svanström, M., 2022. Can carbon fiber composites have a lower environmental impact than fiberglass? Resources, Conservation and Recycling 181, 106234.

Hermansson, F., Janssen, M., Svanström, M., 2019. Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. Journal of Cleaner Production 223, 946-956.

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M.D., Van-Zelm, R., 2016. ReCiPe2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: characterization. RIVM Report 2016-0104. National Institute for Human Health and the Environment, Bilthoven.

Huygens, D., Saveyn, H., Tonini, D., Eder, P., Sancho, L.D., 2019. Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009) - Process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials. Joint Research Centre.

International Organization for Standardization, 2006a. 14040 Environmental management — Life cycle assessment — Principles and framework. Geneva.

International Organization for Standardization, 2006b. 14044 Environmental management — Life cycle assessment — Requirements and guidelines. Geneva.

Kjerstadius, H., Saraiva, A.B., Spangberg, J., Davidsson, A., 2017. Carbon footprint of urban source separation for nutrient recovery. Journal of Environmental Management 197, 250-257.

Labib, T., Hawash, S., El-Khatib, K., Sharaky, A., Diwani, G., Kader, E.A., 2013. Kinetic study and techno-economic indicators for base catalyzed transesterification of Jatropha oil. Egyptian Journal of Petroleum 22, 9-16.

Lafortune, G., Cortés-Puch, M., Mosnier, A., Fuller, G., Diaz, M., Riccaboni, A., Kloke-Lesch, A., Zachariadis, T., Carli, E., Oger, A., 2021. Europe Sustainable Development Report 2021: : Transforming the European Union to achieve the Sustainable Development Goals. France, Paris.

Lebacq, T., Baret, P.V., Stilmant, D., 2013. Sustainability indicators for livestock farming. A review. Agronomy for Sustainable Development 33(2), 311-327.

Linderholm, K., Tillman, A.M., Mattsson, J.E., 2012. Life cycle assessment of phosphorus alternatives for Swedish agriculture. Resources, Conservation and Recycling 66, 27-39.

Liu, G., Li, M., Zhou, B., Chen, Y., Liao, S., 2018. General indicator for techno-economic assessment of renewable energy resources. Energy Conversion and Management 156, 416-426.

Numviyimana, C., Warchoł, J., Khalaf, N., Leahy, J.J., Chojnacka, K., 2022. Phosphorus recovery as struvite from hydrothermal carbonization liquor of chemically produced dairy sludge by extraction and precipitation. Journal of Environmental Chemical Engineering 10(1), 106947.

Pesonen, H.L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z.S., Rebitzer, G., Sonnemann, G.W., Tintinelli, A., Weidema, B.P., Wenzel, H., 2000. Framework for scenario development in LCA. The International Journal of Life Cycle Assessment 5(1), 21-30.

Piccinno, F., Hischier, R., Seeger, S., Som, C., 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. Journal of Cleaner Production 135, 1085-1097.

Raghunath, B., Punnagaiarasi, A., G, R., A, I., Elango, A., Mahesh, G., 2016. Impact of Dairy Effluent on Environment—A Review, Integrated Waste Management in India. pp. 239-249.

Reijnders, L., 2014. Phosphorus resources, their depletion and conservation, a review. Resources, Conservation and Recycling 93, 32-49.

Rodriguez-Garcia, G., Frison, N., Vázquez-Padín, J.R., Hospido, A., Garrido, J.M., Fatone, F., Bolzonella, D., Moreira, M.T., Feijoo, G., 2014. Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant. Science of the Total Environment 490, 871-879.

Rosenström, U., Kyllönen, S., 2007. Impacts of a participatory approach to developing national level sustainable development indicators in Finland. Journal of Environmental Management 84(3), 282-298.

Sartorius, C., 2005. Indicators for a Sustainable Technology Development — A Dynamic Perspective, in: Horbach, J. (Ed.) Indicator Systems for Sustainable Innovation. Physica, Heidelberg, New York, pp. 43-70.

Schröder, J.J., Cordell, D., Smit, A., Rosemarin, A., 2010. Sustainable Use of Phosphorus. Wageningen UR.

Shilpi, S., Seshadri, B., Sarkar, B., Bolan, N., Lamb, D., Naidu, R., 2018. Comparative values of various wastewater streams as a soil nutrient source. Chemosphere 192, 272-281.

Skowrońska, M., Filipek, T., 2014. Life cycle assessment of fertilizers: a review. International Agrophysics 28(1), 101-110.

Slavov, A.K., 2017. General characteristics and treatment possibilities of dairy wastewater - a review. Food Technology and Biotechnology 55(1), 14-28.

Smol, M., Preisner, M., Bianchini, A., Rossi, J., Hermann, L., Schaaf, T., Kruopienė, J., Pamakštys, K., Klavins, M., Ozola-Davidane, R., Kalnina, D., Strade, E., Voronova, V., Pachel, K., Yang, X., Steenari, B.-M., Svanström, M., 2020. Strategies for Sustainable and Circular Management of Phosphorus in the Baltic Sea Region: The Holistic Approach of the InPhos Project. Sustainability (Switzerland) 12(6), 2567.

UNEP, 2009. Guidelines for social life cycle assessment of products.

UNEP, 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021.

Vaccari, D.A., 2009. Phosphorus: A Loomıng Crisis. Scientific American 300(6), 54-59.

Wickerts, S., Arvidsson, R., Sandén, B.A., Peters, G., Hou, L., Albinsson, B., 2021. Prospective Life-Cycle Modeling of Quantum Dot Nanoparticles for Use in Photon Upconversion Devices. ACS Sustainable Chemistry & Engineering 9(14), 5187-5195.

Yapıcıoğlu, P., Yeşilnacar, M.I., 2020. Energy cost assessment of a dairy industry wastewater treatment plant. Environmental Monitoring and Assessment 192(8), 536.

Zhang, F., Wang, Q., Hong, J., Chen, W., Qi, C., Ye, L., 2017. Life cycle assessment of diammonium- and monoammonium-phosphate fertilizer production in China. Journal of Cleaner Production 141, 1087-1094.

Ögmundarson, Ó., Sukumara, S., Herrgård, M.J., Fantke, P., 2020. Combining Environmental and Economic Performance for Bioprocess Optimization. Trends in Biotechnology 38(11), 1203-1214.

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 for fertiliser production coincides with an increase in phosphorus-rich dairy wastewater. These drivers have led to the development of emerging technologies for phosphorus recovery from dairy wastewater with the purpose of generating products that can be used as fertilisers in agriculture. New technologies should be assessed using relevant performance indicators. To identify such indicators, considering the proposed innovative technology in environmental and institutional contexts is necessary. In this study, we developed an approach for identifying and selecting sustainability indicators; the approach was used to derive a list of sustainability indicators specific to the context. Based on a search of relevant literature and interviews with experts, three different tools were developed: a screening framework, a questionnaire for finding actor priorities, and a list of indicator selection criteria. These tools were used to narrow down an initial set of 382 sustainability indicators identified in the literature to 26 that were considered representative and useful for the assessment of the considered innovative conceptual system. The environmental indicators target specifically systems that focus on phosphorus recovery, wastewater and sludge treatment, or agricultural activities, while the techno-economic and social indicators are useful in a broader context, but particularly in early stages of technology development. The novel approach proposed herein that makes use of a screening framework was found to be particularly useful in guiding the selection process; the framework can be easily adapted to different contexts.

Keyword: indicator, sustainability, screening, phosphorus recovery, selection criteria

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 P fertilisers originate are finite and non-renewable (Schröder et al., 2010). The awareness of the scarcity and the increasing demand of this finite resource for fertiliser production caused 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 prioritizes the recovery and safe reuse of P from food and municipal waste flows (European Commission, 2006, 2019). Interest in technical development pertaining to nutrient recovery from organic waste streams has therefore increased in recent years; one potential waste stream to which these technologies can be applied is dairy wastewater (DWW). P concentration is typically higher in DWW than in municipal wastewater (Shilpi et al., 2018).

According to the European Dairy Association (EDA), after the abolition of milk quotas in 2015, the dairy sector increased, with approximately 2.8% annual growth (EDA, 2018; Slavov, 2017). One important aspect, however, is the large volumes of DWW produced (Ashekuzzaman et al., 2019). DWW is a potential source of P that could contribute to addressing the growing demand for food, prevent the decline of phosphate rock resources, and reduce reliance on foreign aid.

To achieve the goal of P recovery in the dairy industry, different technologies for the recovery of P from DWW and subsequent production of fertiliser products are being developed. To guide the exploration of sustainability challenges and opportunities associated with these innovative technologies already at an early stage of development, this study aimed to identify a broad range of indicators for sustainability assessment and select the most appropriate ones.

According to the European Environment Agency (EEA), an indicator is "a measure, generally quantitative, that can be used to illustrate and communicate complex phenomena simply, including trends and progress over time" (EEA, 2005). An indicator can be an important source of information to provide a solid basis for decision-making at different stages of product or process development (Frederiksen and Kristensen, 2008; UN, 1993) ..

The sustainability indicators considered in this study were environmental, techno-economic, and social. Environmental indicators help obtain information related to the release of substances, use of resources, and use of land (EEA, 2000). The anthropogenic pressures on the natural environment manifest themselves as changes in environmental conditions (EEA, 2000). The techno-economic indicators describe the technological basis 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). These social indicators are a set of indicators used to measure progress towards the policy objectives but can also describe the present situation and main challenges, such as poverty and social exclusion (EEA, 2004).

Sustainability indicators are increasingly being seen as important tools in the development of innovative systems. However, useful lists of indicators often need to be developed on a case-by-case basis, since long and generic lists are impractical in terms of providing actionable information. Therefore, guidance on the selection of indicators is required. According to Revi (1998), the characteristics of ideal indicators are easy to find; however, it is not easy to find practical indicators that actually embody these characteristics.

Therefore, this study aimed to identify a broad range of indicators and select a more targeted set for the sustainability assessment of the innovative conceptual system of P products recovery from DWW and the use of the recovered products as fertilisers in farms. This paper describes and explains the identification and selection of these indicators. To provide input for both assessment methods and practice, the following two main questions were formulated to guide the research: (1) What would be a useful approach for identifying and selecting indicators? (2) Which indicators would be useful for sustainability assessment of the innovative conceptual system?

2 General description of the phosphorus recovery system

This study was made within the REFLOW European Training Network (ETN) that focuses on P recovery from DWW (REFLOW ETN, 2019) ; the sustainability indicators will be used for assessment in this specific context. The parts of the full life cycle of products of specific interest primarily cover three sectors: DWW treatment (including sludge treatment), P product recovery, and agricultural activities. Figure 1 illustrates this system and the specific technologies considered. The work to generate an approach for identifying and selecting indicators had, in some respects, a more generic scope and will therefore also be useful in other contexts.

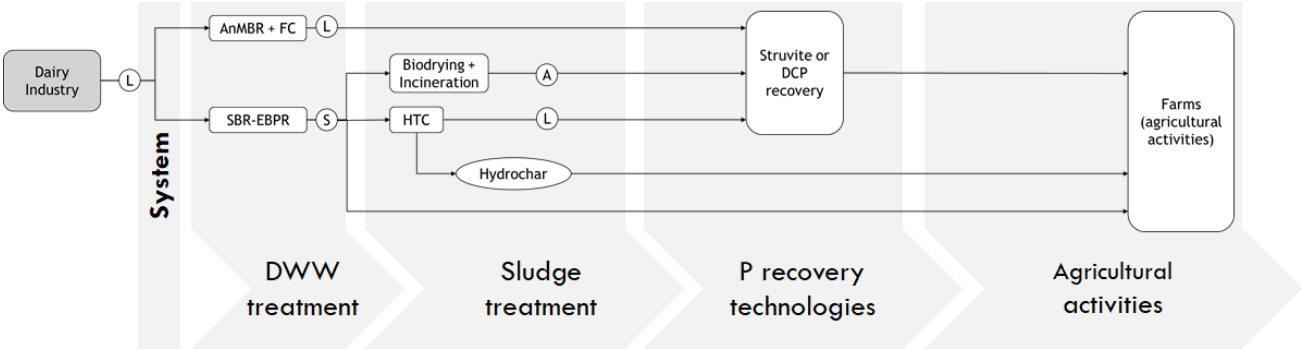

Figure 1 Representation of the considered system for the recovery of P from DWW, showing the recovery from different flows with the REFLOW technologies. P=Phosphorus; DWW=dairy wastewater; AnMBR=Anaerobic membrane reactor; FC=freeze concentration; SBR-EBPR= Sequencing Batch Reactor - Enhanced biological P removal; HTC=Hydrothermal carbonization; DCP= Dicalcium phosphate. The letters represent liquid flows (L), sludge (S), and ash (A) obtained from the different processes and used in the recovery processes or directly in agricultural activities. Processes in the grey box (dairy industry) are not included in the assessment because of the specific focus on guiding technology development in P recovery and product use.

The REFLOW project focused on two experimental options for P recovery in dairy wastewater treatment (DWWT): anaerobic membrane reactors (AnMBR) linked to a freeze concentration step (FC) and a sequencing batch reactor for enhanced biological P removal (SBR-EBPR). The sludge produced from the SBR-EBPR, which is rich in P, is either used to recover magnesium ammonium phosphate (struvite) or dicalcium phosphate (DCP), or directly spread on land. After further hydrothermal carbonization (HTC) of the sludge, the hydrochar can be used as a fertiliser, and P can be recovered from the obtained liquids. Alternatively, after sludge biodrying and incineration, ash can be treated to recover P products. The P products can also be recovered from the P-rich concentrate (liquid) produced by the AnMBR+FC process. Struvite and DCP are produced through precipitation and crystallization. All P-rich products (struvite, DCP, sludge, or hydrochar) can be used as fertilisers in agricultural activities (for further details on the technologies considered, please see the supplementary material (SM; SM1, Section 1). Even if only some specific technologies are focused on, the breadth of the types of technologies considered should make the results more generally applicable for all P recovery in this context and beyond.

Currently, the recovery of P products from DWW and their use as fertiliser in farm activities do not occur at a large scale. Based on the early development stage of the technologies considered, the technology readiness level (TRL) was deemed to be three (TRL=3). As the term indicates, the TRL is a measure to describe the maturity of a technology or the state of its development using a scale of nine levels. At TRL=3, the analytical tests and the laboratory-scale proofs of concept demonstrate the technical feasibility of the innovative system (European Commission, 2014). Although the results obtained are at the laboratory level, the data are assumed to have some relevance regarding efficiency and effectiveness of the full-scale technology.

3 Methodology

3.1 Overall approach

The method approached to answer the two research questions consists of (1) reviewing different scientific and policy documents and reports in order to identify sustainability indicators (2) building a screening framework through a series of interviews with experts, (3) developing an actors' form to collect information about their priorities, (4) reviewing further scientific documents to identify indicator selection criteria, and finally (5) selecting a practical subset of the indicators identified in (1) using the three screening steps based on (2-4). After the screening process, a final refinement and polishing step would allow the selected indicators to fully adapt to the context at hand.

3.2 Identification of sustainability indicators

With the aim of capturing the potential breadth of relevant sustainability considerations and a focus on building on the work of others rather than "re-inventing the wheel", specific documents were consulted to identify an initial list of sustainability indicators. Table 1 lists the sources considered; these include previous compilation in journal papers, technical reports, and European guidelines.

Table 1 Documents reviewed for the identification of indicators for sustainability assessment.

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)

The documents selected for identifying the environmental indicators were mainly life cycle assessment (LCA) review studies and an EU report. Considering that the system we intended to assess is at an early stage of development, we focused on the analysis of LCA review studies that assessed processes or technologies similar to those included in the system of this case study. Behjat et al. (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 supplied a set of indicators. Despite that, further documents were recommended by interviewed experts, primarily European guidelines. The first set of environmental indicators was compiled by reviewing these sources. This approach for identifying the indicators focused on the scope to assess dairy industries, wastewater treatment plants, and fertiliser use in agricultural activities.

No techno-economic assessment of this exact type of system has been published. For techno-economic indicators, literature focusing on the assessment of innovative technologies was sought, and two 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 sources. Ögmundarson et al. (2020) combined indicators from LCA and techno-economic assessment to derive a single decision support tool for the early stages of technology development. Considering that the systems assessed in our study were innovative systems that 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. These studies focus mainly on European economic indicators and indicators of a circular economy.

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. Among the available social evaluation systems, these are most commonly practiced. From this source, it was possible to track and review a UNEP report on Methodological Sheets for subcategories in social LCA. The social indicators suggested in the UNEP guidelines are adopted 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 innovative or not, and in all sectors worldwide, were identified.

The information collected from the review was compiled and assembled to generate the first 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.

3.3 Development of three screening tools

3.3.1 Interviews for framework development

A screening framework can help map the relationships between the explored elements that make up the systems, and the environmental, techno-economic, and social aspects of the entire systems (Ögmundarson et al., 2020). Therefore, such a framework was developed in the specific context of our study. The system shown in Figure 1 form the basis for developing the conceptual framework. As mentioned earlier, the system consists of three sectors, and for sorting and selecting indicators for each sector, three different aspects were considered: material flows, actors, and EU policies.

The elements of each aspect of the framework were identified through a series of interviews with experts. Two different groups of experts were interviewed: 1) researchers working on the technical development of the new technologies, and 2) scientists at the Joint Research Centre (JRC), which is the EU's central scientific research institute.

The first group provides an understanding of how the technologies involved in the processes of the innovative system work. The input and output material flows for each part of the system are also listed. The second set of interviews was based on a technical description of the processes, and provided information on relevant actors, and EU policies. Actors are those who can affect new systems, and who can be provided actionable information in relation to single processes of the system by the indicators (Freeman, 2010; Lyon et al., 2020). The researchers interviewed in the first step can be considered important actors who may benefit from involvement in the selection process, as pointed out by Freeman (2010). 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.

3.3.2 Development of the actors' form

For the sustainability assessment of this conceptual system, which indicators cover the main concerns of the potential actors needs to be known. Therefore, we developed a questionnaire that would allow different actors to prioritise different types of impacts. To avoid overwhelming actors with a large number of indicators or too much detail, broader areas of concern, rather than single indicators, were listed. For listing the 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 of areas of concern for the questionnaire (see SM 1, Section 2 for areas of concern listed in the questionnaire). Ecotoxicity, although was not one of the aspects considered during the first screening, is an indicator regularly used in LCA studies; therefore, it was included in the questionnaire.

This indicator can add value to the hazard and risk assessment of the system, contributing to environmental management. The actors evaluated each area of concern. The environmental and the techno-economic indicators were graded from "not important" to "very important" on a six-grade scale, while the social indicators were ranked from one (least important) to seven (most important). This provided an understanding of the areas that should be prioritised for further indicator selection.

3.3.3 Review of indicator selection criteria

Another tool to narrow down and refine the remaining list of indicators is the application of indicator selection criteria. The selection of indicators has the potential to determine the outcome of optioneering processes; therefore, it is important to have transparent reasoning regarding the criteria for selecting indicators (Lebacq et

al., 2013). To identify and choose the selection criteria, a set of studies proposing lists of indicator selection criteria was reviewed. The selection criteria were assembled, merged, and rephrased to form a new synthesis list to be used during the third screening step. For each criterion, one or more guiding questions were formulated to aid in the selection process.

3.4 Selection process employing the three tools

The three different screening tools that were developed as described in Sections 3.3 were employed consecutively to select indicators from the initial list that had been identified in the literature review described in Section 3.2.

Moreover, as a last step, the units of measurement of the final set of the selected environmental and techno-economic indicators had to be attributed to a specific functional unit (FU), or rather to a reference unit, which is a quantified description of the performance of the system. In addition, some techno-economic and social indicators had to be adapted to the considered system through slight rewording.

3.4.1 First screening: selection based on the framework

The first screening consisted of selecting the indicators using the developed framework. Material flow information were used for the selection of the environmental indicators, while actors and EU policies were used to select techno-economic and social indicators.

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 herein, but can be used when a sorting of that kind is meaningful). The material flows in the generated framework were compared to the environmental indicators in the compiled initial list of indicators, guided by the specific LCIA method of ReCiPe 2016 (Huijbregts et al., 2016). Only the environmental indicators with matching input or output material in the framework were retained.

Techno-economic and social indicators were already sorted into *subcategories* in the reviewed literature, and this grouping of indicators was retained and used in our study, both for the initial coarse screening and for guiding further detailed screening. The techno-economic indicators were sorted into subcategories related to finance, business, and sustainable production and consumption. The social indicators, based on the structure in the UNEP-SETAC guidelines, were categorised based on affected *stakeholders* groups: workers, local community, value chain actors, consumers, society, and children (UNEP, 2021). Various types of social impacts, such as health and safety, technical and economic development, public commitment, transparency, and work conditions, were considered.

In the coarse, first screening, social indicators under the subcategories and stakeholders that were irrelevant to the system and the context considered for this case study were removed (e.g., “children” from stakeholders). 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 the kind of information on possible consequences of activities in the system that could enable the actors in the framework to make decisions relating to the further development of elements in the system. Moreover, social indicators with a clear 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.

3.4.2 Second screening: selection based on the actors' form

The developed actors' form was used to identify the areas of indicators that covered the main concerns of the actors. At the ESPC4[1] conference and PERM5[2] meeting in June 2022 in Vienna, Austria, 18 actors responded to the survey (see SM1 Section 6 for their general affiliations) providing their priorities for the assessment of the considered system. Their priorities were then used in the second screening of indicators to select indicators in areas of high concern and remove others. Only three or four areas of concern considered of higher importance by the actors were included.

3.4.3 Third screening: selection based on criteria selection

Finally, the remaining list of indicators was screened based on the selection criteria. Indicators were selected by considering the questions defined for each criterion. Indicators that did not meet the selection criteria were excluded.

4 Results and discussion

In this section, results from the indicator identification (section 4.1), the selection approach tools development (section 4.2) and the indicator selection process (section 4.3) will be provided and discussed.

4.1 First compiled list of indicators

An initial list of 382 indicators was compiled (SM 2) by reviewing the documents. The list was narrowed down to 230 indicators (SM 2) by removing duplicates. This large set of indicators was further refined through screening steps based on the use of the three developed tools: framework, actor priorities, and selection criteria.

4.2 Tools developed for the indicator selection

4.2.1 Screening framework

Material flows, actors, and policies collated through the interviews with technical researchers and JRC scientists (see SM 1 Section 4 for more details about material flows and EU policies) were placed in the different parts of the innovative conceptual system represented in Figure 1 to generate a framework that would guide the first screening (see Figure 2).

Although this framework was developed to select indicators for the sustainability assessment in this specific case study, it can likely be used for the assessment of different but similar systems. The framework was developed on the basis of the knowledge of experts in the sectors involved in the system intended to be assessed. The framework can 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.

[1] The European Sustainable Phosphorus Conferences bring together companies, stakeholders, regional and national authorities, and researchers, to discuss phosphorus and nutrient sustainability actions and policies.

[2] This meeting linked science, industry, agriculture, and policy makers in addressing the ways by which the uptake of project recommendations can be increased policy makers and marketed for users, and identified perspectives for research and policy, as well as implementation gaps.

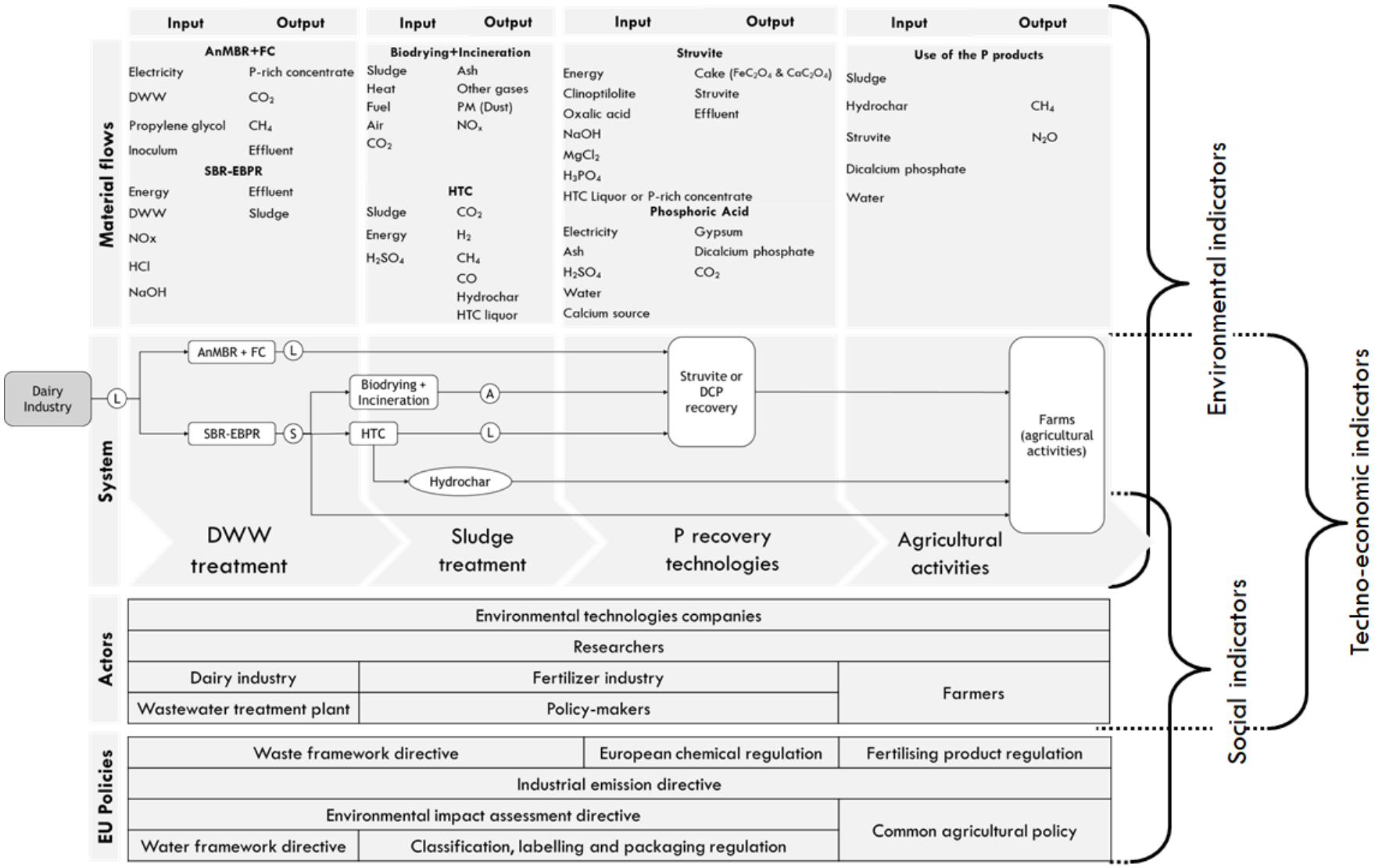

Figure 2. Framework describing material flows, actors, and EU policies that are linked to the technical aspects of the considered systems and their relation with the environmental, techno-economic, and social indicators.

4.2.2 Actor priorities

Figure 3 presents the average of the actors' priorities for sustainability assessment of the considered system.

As shown in Figure 3, there was great interest among the responding actors for assessing *ecotoxicity, climate change*, *eutrophication*, and *energy use.* Lower importance was assigned to *acidification*, *land use*, and *water use*. Actors affiliated with universities and governmental institutions considered climate change to be very important. However, companies and research institutes placed a higher priority on ecotoxicity and ecosystem changes.

Regarding the techno-economic assessment, to perform nutrient recovery and introduce novel materials into the market, economic decisions must be taken by the concerned sectors. For instance, decisions regarding investments in technologies, finance mechanisms, and the relevant rate of return on investment must be made. From the participating actors' perspective, the most relevant areas of concern for P recovery from waste sources according to our survey are shown in Figure 3. There was a particular interest among the respondents in assessing the *rate of return*, or rather the gains or loss of an investment over a period of time, *existing market*, which is the amount of ongoing trade of output, and *risk* due to variations in the return. The majority of actors considered the existing market important.

The process of nutrient recovery from dairy wastewater and the use of the final recovered products provide various social benefits and impacts. Based on the responding actors' interests, the a*ssessment of consumer health, safety, and satisfaction of final products* and *capacity to engage local actors for market development* are the most relevant areas of concern for assessing social impacts (see Figure 3). The first one is considered "most important" by the members of academies, governmental organizations, and companies, while research institutes prioritize the second.

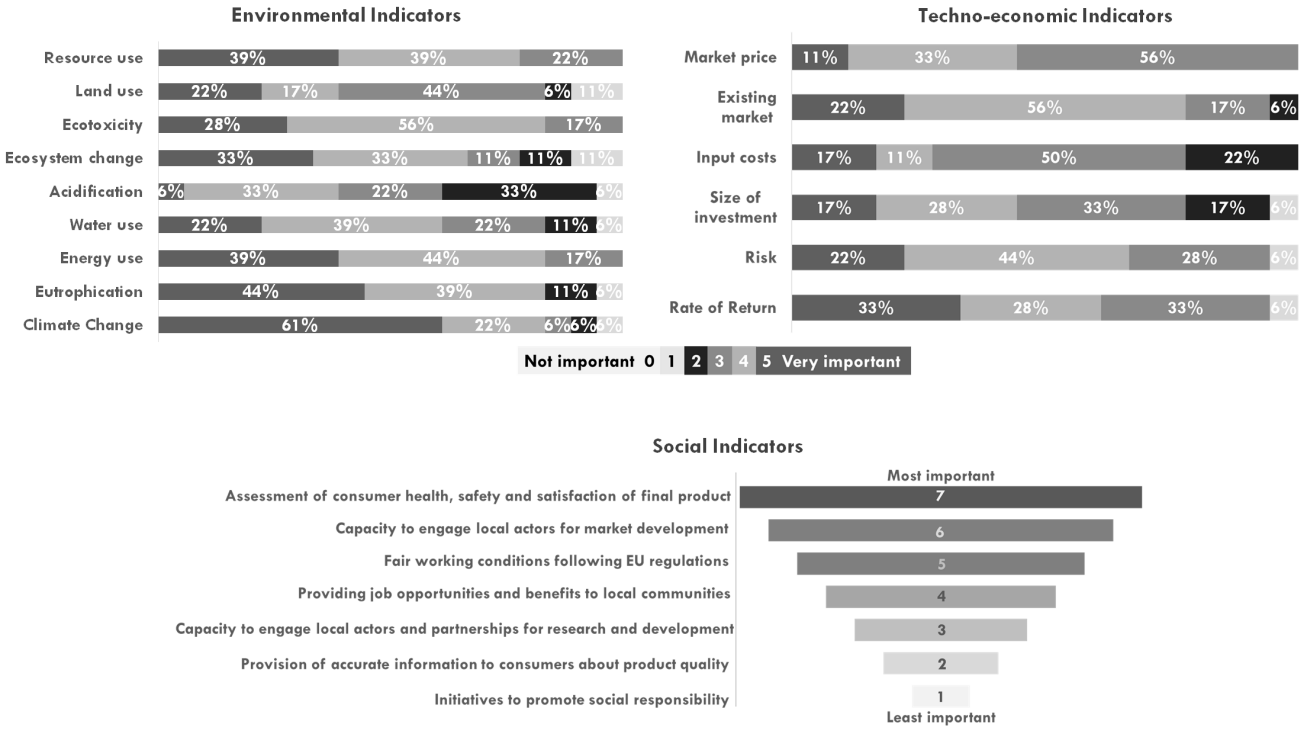

Figure 3 Response to questionnaire by actors ranking the importance of different environmental, techno-economic, and social aspects. The environmental and techno-economic areas of concern are graded from "very important" to "not important," while the social areas are ranked from 7 ("most important") to 1 ("least important").

4.2.3 Criteria for indicator selection

The reviewed studies proposed and used selection criteria for choosing sustainability indicators from 1998 to the present. Despite the passage of time, both previous and recent studies have employed similar sets of criteria. Many selection criteria have been proposed (see SM 1 and Section 5 for the complete list), but the importance given to each depends on the context of the assessment. Comparing these studies, a set of selection criteria most frequently preferred for technology sustainability assessment were selected (Table 2) and adapted to the system considered in this study. The criteria selected and listed in the table are the most commonly considered indicator selection criteria in the reviewed studies; however, these have been subjected to some regrouping and adaptation. The criteria *geographic boundary* and *policy responsiveness,* for this case study were limited to Europe. Europe was chosen because the REFLOW ETN project aims to support decision-making in European regions. *Practicability* and *quality* are criteria that concern data resources; quantitative and measurable data need to be available. The questions formulated for each selection criterion were 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.

4.2.4 Discussion on developed approach

One drawback of this approach is an element of subjectivity. However, this is inevitable when classifying sustainability indicators for specific scenarios. The approach aiming at the optimal solution to select representative indicators for the considered system, might not work in all contexts. However, the framework and survey are appropriate tools to know more about the technologies and actors' opinions and be aware of all problems and required information for the assessment of different systems. The use of these tools ensures exploring the interaction between the processes of the system and the actors, which opinions will guide the technical development of the system.

Furthermore, to be able to use the selected sustainability indicators in a multicriteria analysis context, more work on the methodology is needed beyond what has been done here. Weighting sustainability indicators is necessary for handling case-specific trade-offs, and this research aspect requires considerable further work such as a future multicriteria analysis (MCA) of the system. The MCA, which includes all the three different sustainability dimensions (environmental, techno-economic, and social) will contribute to the technical development of emerging systems.

Table 2 Assembled sustainability indicator selection criteria and their appearance in different sets of criteria in literature. For each selected (and sometimes modified) criterion, some questions were elaborated for guidance in the indicator selection step.

Criteria	Description	Questions	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)
Practicability	The indicator should be based on measurable data available when needed.	▪ Are there enough information and data to allow the use of this indicator? ▪ Are timely data available for this indicator?	✓	✓	✓	✓	✓	✓	✓	✓
Quality	The indicator should be based on accurate and robust data, consistent over time.	▪ In order to use this indicator, is there sufficient information based on accurate and robust data?	✓	✓	✓	✓		✓	✓	✓
EU policy responsiveness	The indicator is capable of providing evidence that the development of the system is responsive to EU policies	▪ Is this indicator responsive to EU policies?	✓		✓	✓			✓	✓
Geographical scope	Indicators need to be allocated and matched to a specific geographic area; for this specific case study, Europe.	▪ Does this indicator provide a sufficient level of cross-European country comparability? ▪ Does the scope of the indicator match the geography in question?		✓	✓	✓			✓	
Guiding	The indicator should provide information in time to act on it, and it should be able to guide future actions.	▪ Does this indicator provide information about how to move forward for sustainability improvement?	✓		✓	✓				
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.	▪ Is the indicator adaptable and applicable to a range of systems of different sizes and types? ▪ Is the indicator sufficiently universal for comparison across regions?	✓	✓		✓	✓	✓		✓
Participatory	The indicator should be accessible to users, and easy to understand before to be used for decision making.	▪ Is the indicator accessible to different users? Is the indicator "comprehensible"?	✓		✓	✓	✓	✓		✓
Representativeness	The indicator should be appropriate to the context, or system which it intends to indicate and be able to provide an early warning of potential problems.	▪ Is the indicator appropriate to the context which it intends to indicate? ▪ Does this indicator provide information about how the new systems will impact the environmental, economic, and social spheres?		✓	✓	✓	✓	✓	✓	✓

4.3 Results of the screening processes

From the review of all the documents, after removing duplicates, the 230 remaining indicators were subjected to further screening to obtain a final list of 26 indicators. Table 3 presents an overview of the number of indicators suggested in the literature and those finalised through the screening in the three steps, for each indicator category.

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

Indicators	Literature Review	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

4.3.1 First screening

Through the first screening process, a set of 230 indicators was narrowed down to 102 (the specific indicators selected are provided in SM2).

From the detailed analysis of each process in the technical system, 13 environmental indicators were selected from the 24 indicators collected during the review process (after removing duplicates). These indicators are connected to the material flows used or produced during the use of the technologies.

Of the 37 techno-economic indicators included in the first compiled list, 19 were relevant within the framework. These are the indicators considered relevant to the actors of each process in the system.

Regarding the social indicators, 70 of 169 indicators corresponded to the elements of the framework. These are the indicators considered relevant to both the actors and the EU policies of each process in the system.

4.3.2 Second screening

Through the second screening process applied by using the results of the questionnaire, a set of 102 indicators was narrowed down to 60 (for specific indicators that were selected, please see SM2).

According to the questionnaire results, as previously reported, ecotoxicity is an area of concern that should be considered. However, based on the results of the LCIA analysis applied as part of the framework development, ecotoxicity does not seem to be a significant environmental impact, so it was not selected, except with regard to the specific concern related to particulate matter. The indicators selected in the second screening, were those classified under the areas of concern of climate change, eutrophication potential, energy use, and resource use, also including the indicator particulate matter formation. In total, 7 of the 13 environmental indicators were selected during the second screening.

Among the techno-economic indicators, 11 of the 19 indicators were selected during the second screening, using the results of the questionnaire.

Also, 42 out of the 70 social indicators were selected based on the results of the questionnaire. All the indicators under the areas of concern considered important based on the results of the questionnaire were selected; however, 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 more local actors, who can influence or be affected based on the different decisions taken during

the development of the system at an early stage. Furthermore, our case study is part of the ongoing REFLOW ETN project, which engages different actors in market development. Therefore, despite the results of the questionnaire, we have evidence that this area of concern is a significant aspect in the context of the present study.

4.3.3 Third screening

The final list of indicators comprised those remaining after the use of the selection criteria, compiled and reported in Table 2. Through this third screening process, a set of 60 indicators was narrowed down to 26.

Environmental indicators

All the environmental indicators selected by the second screening were maintained after the third screening (see Table 4); all of these indicators were considered essential in terms of providing further information about the environmental effects of the system. The data required to assess the environmental impact using these indicators were considered available and easy to collect and therefore responded to the criteria of *practicability,* and *quality.* Furthermore, these indicators were the right instrument to verify whether the system is in line with the EU directives (see Section 4.3 in SM1 for the EU policies considered); hence, these indicators were *EU policy responsive*. In addition, the results obtained using these indicators are important to *guide* future actions in system development. Table 4 reports the final selected environmental indicators and the units suggested by the listed LCIA methods. These units were attributed to the mass of the final recovered product, struvite, or dicalcium phosphate, which is the most common and recommended FU to be considered (Amann et al., 2018). A set of reviewed LCA studies propose 1 kg of the P-rich product recovered as the FU.

Table 4 Environmental indicators selected for the assessment of the system focused on 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 are related to the proposed functional unit (FU) of 1 kg of the 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 $PM_{2.5}$	ReCiPe 2016 v1.1
Fossil depletion	kg oil eq	ReCiPe 2016 v1.1
Mineral depletion	kg Sb eq	CML 2002

Techno-economic indicators

Through the third screening, a list of 11 techno-economic indicators was reduced to a list of seven indicators (see Table 5). These seven indicators were mainly selected because apart from meeting most of the eight common criteria, they were the most easily described with physical units. These indicators met the criteria of *practicability, guiding,* and *adaptable and representative.* Furthermore*,* they were also accessible to different users and were easy to understand and use for decision-making, thereby meeting the criterion of being *participatory.* Unlike the environmental indicators, this set of techno-economic indicators can be adapted and used for the assessment of different systems in early stages of development (TRL=3).

Table 5 Techno-economic indicators selected for the assessment of the system focused on P recovery from dairy wastewater (DWW) for fertilizer use. The units of measurement adopted and attributed to the final proposed functional unit (FU) of kg of the recovered product. The indicators are classified into three subcategories. Some indicators have been slightly modified so as to be focused 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	€/year
	Gross profit	profit/year
	Simple Rate of Return on Investment	%
Techno-economic cost	Payback time	time
Business indicators	~~Industrial~~ **REFLOW system** producer prices	**€**
	~~Industrial~~ **REFLOW products** production	**mass/month**

Social indicators

Forty-two social indicators were whittled down to 12 using indicator selection criteria. The main criteria met by these indicators (listed in Table 6) were *guiding*, *EU policy responsive*, and *participatory*. 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 experiment in the laboratory. However, this is believed to be well regulated.

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

Stakeholder	Subcategories	Social indicators [Area of interest]
Workers	Smallholders including farmers	Participation ~~in~~ **of** farmers' organization **in the design process** [Inclusiveness]
		~~Evidence~~ **Estimation** of crop yield [Productivity]
		~~Evidence~~ **Estimation of the evidence** of 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 ~~with the organization~~ **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 ~~organization~~ **of system** ~~obtained~~ 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

4.3.4 Discussion on final compilation of selected indicator

The selected sustainability indicators are specific for a TRL at 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.

Moreover, although these indicators met the criterion of *geographical scope*, this does not mean that they are easily applicable to all European regions. The EU policies listed in the framework 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. On the contrary, the directives must be incorporated by EU regions into their national legislation. These directives require EU regions to adopt measures 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 to allow the application of these indicators in different regions of Europe.

Interestingly, among all the indicators in the final list, indicators that considered 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 were not captured by the indicator identification process (Bertanza et al., 2015)

Nevertheless, further research is needed to: explore the potential interactions between the selected indicators and the system to implement these indicators in relation to technology assessment; and include indicators that reflect on the local authorization aspects.

5 Conclusions

This study presents one example of how a set of sustainability indicators is identified and selected to assess an innovative conceptual system – phosphorus recovery from dairy wastewater for use as fertiliser in agriculture; the purpose was to impart knowledge and guidance for obtaining a list of sustainability indicators for the assessment of a specific system in the early stages.

The first list of sustainability indicators was identified by reviewing a set of documents. 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 the literature and interviews, and the application of this method was demonstrated. The approach comprised three steps for which tools were developed within this work: a framework based on flow identification and expert interviews for the first step; a questionnaire on actors' priorities for the second step; and 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, will have a specific focus on technologies at TRL = 3.

Using the three tools, a set of indicators was narrowed down from 230 to 26. Among the selected indicators, although the environmental indicators are specific for the case considered in this study, the techno-economic and social indicators will also have a focus on product life cycles which involve sectors other than those mentioned in this study.

The findings of this study are verifying that 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 exist, the proposed approach and its selection tools can be useful for the selection of the most relevant sustainability indicators for a specific case.

Acknowledgments
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6 References

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resources, Conservation and Recycling 130, 127-139.

Arvidsson, R., Baumann, H., Hildenbrand, J., 2015. On the scientific justification of the use of working hours, child labour and property rights in social life cycle assessment: three topical reviews. The International Journal of Life Cycle Assessment 20(2), 161-173.

Ashekuzzaman, S.M., Forrestal, P., Richards, K., Fenton, O., 2019. Dairy industry derived wastewater treatment sludge: Generation, type and characterization of nutrients and metals for agricultural reuse. Journal of Cleaner Production 230, 1266-1275.

Baldassarri, C., Allacker, K., Reale, F., Castellani, V., Sala, S., 2017. Consumer Footprint. Basket of Product indicators on Housing. Joint Research Centre.

Behjat, M., Svanström, M., Peters, G., 2022. A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater. Journal of Cleaner Production 369, 133307.

Bertanza, G., Canato, M., Laera, G., Tomei, M.C., 2015. Methodology for technical and economic assessment of advanced routes for sludge processing and disposal. Environmental Science and Pollution Research 22(10), 7190-7202.

EASAC, 2016. Indicators for a circular economy. German National Academy of Sciences, Germany.

EC, 2001. GUIDING PRINCIPLES FOR THE SELECTION OF INDICATORS AND STATISTICS, in: Committee, S.P. (Ed.).

EDA, 2018. Economic report 2017/18. EDA (European Dairy Association).

EEA, 2000. Environmental indicators: Typology and overview.

EEA, 2004. EEA Glossary - Social indicator. http://europa.eu.int/comm/employment_social/news/2001/oct/i01_1395_en.html. October 2022).

EEA, 2005. EEA core set of indicators - Guide. European Environment Agency, Luxemburg: Office for Official Publications of the European Communities.

European Commission, 2006. Draft reference document on best available techniques in the food, drink and milk industries. JRC, Seville.

European Commission, 2014. Technology readiness levels

European Commission, 2019. Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) - JRC118627. Publications Office of the European Union, Luxembourg.

European Commission, 2020. COM/2020/474 final Critical Raw Material Resilience: Charting a Path towards greater Security and Sustainability.

European Commission, 2022. Types of EU law. https://ec.europa.eu/info/law/law-making-process/types-eu-law_en. (Accessed December 2022).

EUROSTAT, 2009. Principal European Economic Indicators - A statistical guide. European Comission, Luxembourg: Office for Official Publications of the European Communities.

Frederiksen, P., Kristensen, P., 2008. An indicator framework for analysing sustainability impacts of land use change. Sustainability Impact Assessment of Land Use Changes, 293-304.

Freeman, R.E., 2010. Strategic Management: A Stakeholder Approach. Cambridge University Press, Cambridge.

Goedkoop, M., Indrane, D., de Beer, I., 2018. Handbook for Product Social Impact Assessment 2018.

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M.D., Van-Zelm, R., 2016. ReCiPe2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: characterization. RIVM Report 2016-0104. National Institute for Human Health and the Environment, Bilthoven.

International Organization for Standardization, 2006. 14044 Environmental management — Life cycle assessment — Requirements and guidelines. Geneva.

Labib, T., Hawash, S., El-Khatib, K., Sharaky, A., Diwani, G., Kader, E.A., 2013. Kinetic study and techno-economic indicators for base catalyzed transesterification of Jatropha oil. Egyptian Journal of Petroleum 22, 9-16.

Latruffe, L., Diazabakana, A., Bockstaller, C., Desjeux, Y., Finn, J., Kelly, E., Ryan, M., Uthes, S., 2016. Measurement of sustainability in agriculture: a review of indicators. Studies in Agricultural Economics 118, 123-130.

Lebacq, T., Baret, P.V., Stilmant, D., 2013. Sustainability indicators for livestock farming. A review. Agronomy for Sustainable Development 33(2), 311-327.

Liu, G., Li, M., Zhou, B., Chen, Y., Liao, S., 2018. General indicator for techno-economic assessment of renewable energy resources. Energy Conversion and Management 156, 416-426.

Lundin, M., Molander, S., Morrison, G., 1999. A set of indicators for the assessment of temporal variations in the sustainability of sanitary systems. Water Science and Technology 39, 235-242.

Lyon, C., Cordell, D., Jacobs, B., Martin-Ortega, J., Marshall, R., Camargo-Valero, M.A., Sherry, E., 2020. Five pillars for stakeholder analyses in sustainability transformations: The global case of phosphorus. Environmental Science & Policy 107, 80-89.

Mascarenhas, A., Nunes, L.M., Ramos, T.B., 2015. Selection of sustainability indicators for planning: combining stakeholders' participation and data reduction techniques. Journal of Cleaner Production 92, 295-307.

Nathan, H.S.K., Reddy, B.S., 2010. Selection criteria for sustainable development indicators. Mumbai: Indira Gandhi Institute of Development Research.

REFLOW ETN, 2019. THE PHOSPHORUS RECOVERY FOR FERTILIZERS FROM DAIRY PROCESSING WASTE. https://etn-reflow.eu/. (Accessed October 2022.

Revi, A., 1998. Indicators and information systems for sustainable development.

Roy, R., Chan, N.W., 2012. An assessment of agricultural sustainability indicators in Bangladesh: review and synthesis. The Environmentalist 32(1), 99-110.

Schröder, J.J., Cordell, D., Smit, A., Rosemarin, A., 2010. Sustainable Use of Phosphorus. Wageningen UR.

Shilpi, S., Seshadri, B., Sarkar, B., Bolan, N., Lamb, D., Naidu, R., 2018. Comparative values of various wastewater streams as a soil nutrient source. Chemosphere 192, 272-281.

Skowrońska, M., Filipek, T., 2014. Life cycle assessment of fertilizers: a review. International Agrophysics 28(1), 101-110.

Slavov, A.K., 2017. General characteristics and treatment possibilities of dairy wastewater - a review. Food Technology and Biotechnology 55(1), 14-28.

UN, 1993. Agenda 21 :programme of action for sustainable development, Rio Declaration on Environment and Development, statement of forest principles : the final text of agreements negotiated by Governments at the United Nations Conference on Environment and Development (UNCED), 3-14 June 1992, Rio de Janeiro, Brazil, in: Information, D.o.P. (Ed.). UN, New York.

UNEP, 2009. Guidelines for social life cycle assessment of products.

UNEP, 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021.

Ögmundarson, Ó., Sukumara, S., Herrgård, M.J., Fantke, P., 2020. Combining Environmental and Economic Performance for Bioprocess Optimization. Trends in Biotechnology 38(11), 1203-1214.

Supplementary material 1 - Sustainability indicator identification and selection for an innovative conceptual system: phosphorus recovery from dairy wastewater

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Table of Contents

1 Description of the technologies in the system

The elements and description of the technologies implicated in the system were identified through a series of interviews with experts.

1.1 The Sequencing batch reactor for enhanced biological phosphorus removal

The SBR-EBPR is a technology which consists of a single batch reactor where the DWW is treated before being discharged, in order to remove undesirable components. Filling, different aeration stages, settling and withdraw phases can all be achieved using this sole batch reactor. The duration of each stage can be adjusted according to the treatment requirements. Particularly for this project, the SBR system will be configured so as to promote and maintain phosphorus accumulating organisms (PAOs) and denitrifying phosphorus accumulating organisms (DPAOs) communities which will be responsible for P recovery and N removal. These cultures need alternating anaerobic/aerobic/anoxic environments (see Figure 1). The configuration of the different stages will be adjusted to optimize their growth and activity.

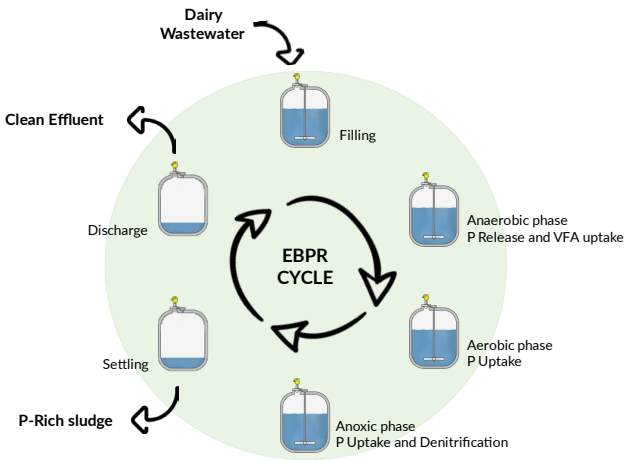

Figure 1 Representation of the SBR-EBPR reactor during once complete cycle.

1.2 The Anaerobic membrane reactor and Freeze Concentration

The AnMBR is coupled with the FC operation for the treatment of the liquids emitted from the dairy industry, DWW, including also whey. The output of this coupled technology is a concentrated P effluent. An AnMBR technology can be described as fundamentally a biological treatment process operated without oxygen and employing a membrane system. The AnMBR reactor will be operated under mesophilic conditions (37 ± 0.2 °C) with a mechanical stirring to provide semi-continuous mixing. Peristaltic pumps are used to add and decant the effluent. The effluent (digestate) from the anaerobic reactor will be pumped into the feed tank, then the feed stream is pumped to the membrane module. Afterwards, the feed stream flows tangentially over the surface of the membrane filter. Some of the feed stream will permeate through the membrane, while the rest will continue to flow through the system as a concentrate. The permeate will be collected for the FC operation, while the concentrate will be pumped back to the reactor. The FC technology is a solid-liquid separation unit operation, where the solution is cooled down and then concentrated by separating pure ice crystals during the freezing process. The objective of the combination of these two technologies is to produce a concentrated effluent which is expected to be 90% of recovered P (Figure 2).

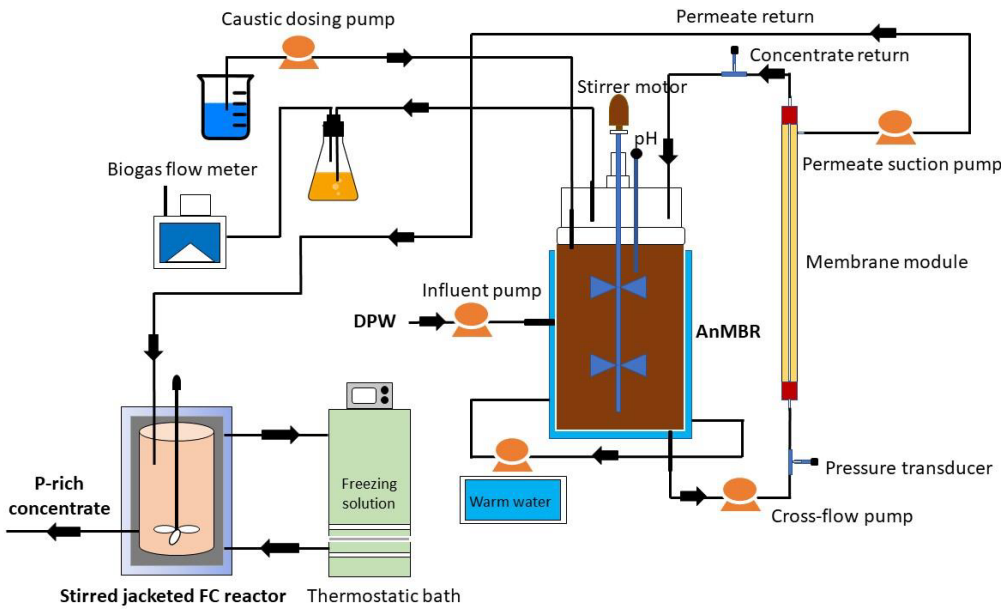

Figure 2 Proposed coupled technology of AnMBR+FC.

1.3 The Hydrothermal Carbonization

HTC is considered one of the promising thermochemical techniques that allows for the concentration and extraction of phosphorus from dairy wastewater. Thermochemical treatment of waste has been proven to allow for the transformation of energy, as well as the recovery of valuable nutrients such as phosphorous. The main aim of thermochemical treatment is to upgrade the carbonaceous material in the solid products, in addition to the concentration of nutrients in both the solid and liquid products. During HTC, organic waste undergoes a series of reactions on the path of transformation into hydrochar, including hydrolysis, dehydration, decarboxylation, polymerization and aromatization. (Reza et al., 2014). The final products of HTC are the hydrochar, a carbonaceous structure with coal-like properties having higher calorific value than initial biomass, and liquor, which consists mainly of sugars, organic acids such as acetic acid, levulenic acid, formic acid and lactic acid, and phenolic compounds such as phenol, cresol, and furfurals.

1.4 Biodrying

The main purpose of the biodrying is to reduce the material's moisture while retaining nutrients for further agronomic valorization. The biodrying reactor (operative volume of 100 L) will be fed by the P-rich EBPR bio products (P-rich sludge). The reactor is made with steel, but internally the lateral walls are insulated with stone wool to avoid the loss of temperature and maintain adiabatic conditions. It consists of a monitoring and controlling equipment, composed by an air flowmeter, oxygen and carbon dioxide sensor, and temperature probe. The process temperature monitoring is carried out by using multipoint temperature sensing probes placed at different locations along the height of the reactor unit.

1.5 Incineration

Sludge incineration is the most accepted alternative end disposal method after land spreading. This process consists of an oxidative method, converting the organic carbon, nitrogen, sulfur and phosphorus into mineral solid products. The incineration process is effective in eliminating the feed organics, produces little odor (provided the flue gas treatment is effective), and generates a solid ash product which is stable and substantially reusable. The heat generated can be recovered from the flue gas stream and reused directly and/or converted to electrical power. On the other hand, it destroys potentially useful organic matter and emits carbon dioxide gas to the atmosphere. Sludge incineration reactors are predominantly configurated as fluidized beds (Judd, 2022).

1.6 Struvite precipitation

This process consists of a initial batch reactor where the adjustment of pH uses aqueous sodium hydroxide solution (6 M NaOH) and hydrochloric acid (1 M HCl) to exact pH 8.9 ± 0.1 (Numviyimana et al., 2021). At the same moment the molar ratio of calcium, magnesium and ammonium to P is adjusted (Numviyimana et al., 2021). The reactor is stirred at a rate between 60 and 100 rpm for between 60 min and 1h in order to achieve liquid-solid phase equilibrium (Numviyimana et al., 2020; Numviyimana et al., 2021).The phases are then separated by filtration with vacuum pump and the washed precipitate is dried at room temperature. The dry product is then dissolved in citric acid solution (1:100) (Numviyimana et al., 2020).

1.7 Dicalcium phosphate production

This technology consists in two processes (see Figure 3): the attack stage and the precipitation stage. In the first stage ash is treated with adding diluted sulfuric acid and calcium source, in order to produce monocalcium phosphate (MCP), calcium sulphate dihydrate, and some impurities. The MCP is further treated with additional Calcium sources, to obtain dicalcium phosphate (DCP). These processes are chemical beneficiation processes with a recovery efficiency far above any traditional beneficiation plant (up to 90%). This kind of technology is used to treat and upgrade low-grade secondary raw materials, as ash, producing DCP mainly used to produce phosphoric acid (Prayon, 2022).

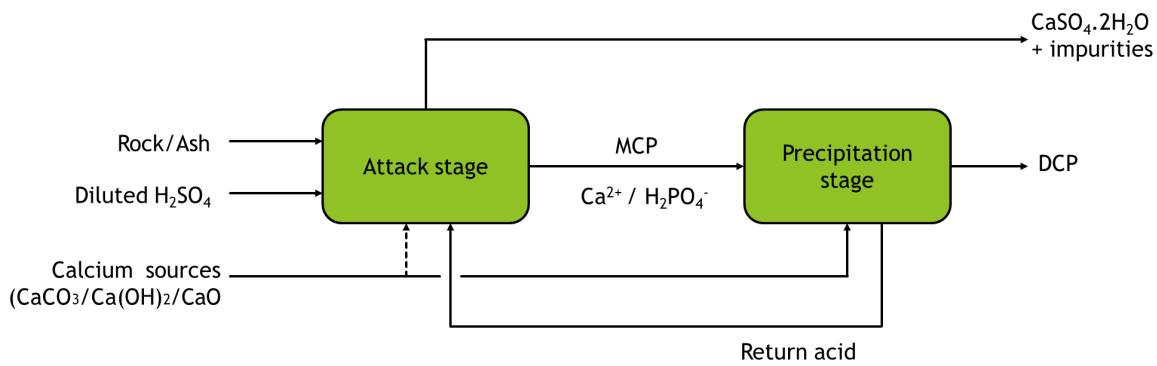

Figure 3 Representation of the dicalcium phosphate (DCP) formation process.

2 Actors' form

RE|FLOW
EUROPEAN TRAINING NETWORK

Stakeholder form

ESPC4-PERM5 20 – 23 June 2022, Vienna

The recovery of nutrient rich products from waste and by-products represents several challenges associated with technology development, production, safe use and market inclusion. They can potentially substitute raw materials such as P-rock and have a potential use as fertilisers, liming materials, soil improvers, among others. However, the development of these new products constitutes a challenge from a sustainability perspective. Techno-economic, social, and environmental indicators are used to assess the feasibility of recovering nutrient rich products from sectors such as municipal, dairy, slaughterhouses, etc.

This survey is designed by REFLOW ETN which aims for the recovery of P-rich materials from the dairy industry and the objective **is to know your perspective on the relevance of sustainability indicators and business models for the deployment of our nutrient recovery technologies and safe use of final products.**
The survey lasts around 10 minutes and the information provided is strictly anonymous and will be used as part of academic research. If you have any question, please communicate with: reflow.eu@gmail.com

1. Please enter the name of the organization that you represent (voluntary question):

   .....

2. Which type of organisation is this?

   ☐ Company

   ☐ Academia

   ☐ Governmental

   ☐ Branch organisation

   ☐ Other:.....

3. In which area/areas are your organization active?

   ☐ Wastewater treatment facilities

   ☐ Waste management operator (Sludge treatment, waste disposal)

   ☐ Technology development

   ☐ Agricultural sector (advisors, farmer cooperative or similar)

   ☐ Fertiliser organization

   ☐ Dairy industry

   ☐ Other:.....

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Sustainability indicators (5 minutes)

4. The recovery of nutrients is associated with environmental impacts during the development of the technology, recovery of materials and use in agriculture. There are several indicators available to measure environmental impacts. Among the following, which of the indicators would you consider relevant for the development of nutrient recovery technologies and use of recovered materials? Please evaluate the level of importance from 0 (not important) to 5 (very important).

	Not important					Very important
Climate change (Increased levels of atmospheric carbon dioxide produced by the GHGs emissions)	0	1	2	3	4	5
Eutrophication (Excessive richness of nutrients in body of water which causes a dense growth of plants)	0	1	2	3	4	5
Energy use (Process of using energy, or the amount of energy that is used)	0	1	2	3	4	5
Water use (Process of using water, or the volume of water that is used)	0	1	2	3	4	5
Acidification (Decreases of the pH by the presence of NOx and SOx)	0	1	2	3	4	5
Ecosystem change (Change of biological community, organisms´ interactions and their physical environment)	0	1	2	3	4	5
Ecotoxicity (toxic effects, caused by natural or synthetic pollutants, to the constituents of ecosystems)	0	1	2	3	4	5
Land use (Areas used for residential, industrial or commercial purposes, for farming or forestry, etc.)	0	1	2	3	4	5
Resource use (The removal and use of raw materials, from the natural environment)	0	1	2	3	4	5

5. To perform nutrient recovery and introduce novel materials into the market, decisions in economics must be taken by interested sectors. For instance, the investment in the technologies, finance mechanisms and return of investment. From your perspective, which of the following indicators are the most relevant for the recovery of nutrients from waste sources (ex. sludges)? Please evaluate the level of importance from 0 (not important) to 5 (very important).

	Not important					Very important
Rate of return (gains or losses of an investment over a period of time)	0	1	2	3	4	5
Risk (variation of the return)	0	1	2	3	4	5
Size of investment (minimal investment needed)	0	1	2	3	4	5
Input costs (cost of spent resources in production)	0	1	2	3	4	5
Existing market (amount of ongoing trade of output)	0	1	2	3	4	5
Market price (characteristic of output market)	0	1	2	3	4	5

6. The process of nutrient recovery from waste will imply the interaction of societal aspects such as local communities, new employment generation, use of final fertilising products, etc. Based on your expertise, how relevant are the following indicators for society? Please rank them from 1 (least important) to 7 (most important). Please note that you can NOT repeat numbers 1 to 7.

- ☐ Assessment of consumer health, safety, and satisfaction of final products
- ☐ Providing job opportunities and benefits to local communities
- ☐ Fair working conditions (salary and wages, social benefits, opportunities for growth, adequate environment for working conditions) following EU regulations.
- ☐ Initiatives to promote social responsibility along the supply chain
- ☐ Provision of accurate information to consumers about product quality, benefits, productivity, and risks of the use of new technologies and fertiliser products.
- ☐ Capacity to engage local actors for market development (technology providers, product distributors, industry, farmers, etc.)
- ☐ Capacity to engage local actors and partnerships for research and development of recovered materials (technology providers and use)

7. Which of the following issues are from your perspective important to assess during a sustainability analysis of the conceptual REFLOW system? (all sustainability together). Please rank them from 1 (least important) to 7 (most important). Please note that you can NOT repeat numbers 1 to 7.

- ☐ Environmental impact (eutrophication, acidification, global warming, toxicity)
- ☐ Resources Use (energy, water, energy, fossil fuels)
- ☐ Investment costs, financing, and positive business cases for interested sectors
- ☐ Stable market outlook for new products (clients, supply, demand, competitors, availability)
- ☐ Adequate working conditions and regional development of local actors
- ☐ Market inclusion of products with stable quality, yield benefits and low risks for use
- ☐ Others, please specify and motivate in question no. 8

8. Are there other issues that you think are important and would like sustainability assessment to be able to answer?

.....

.....

.....

Thank you very much for your participation! Would you help us further with our research? Leave here you contact details:

....

3 Life cycle impact assessment

According to LCA methodology, environmental indicators are categorised in three subcategories: human health, ecological consequences (ecosystem and biodiversity) and resources depletion. These three subcategories are called endpoints, while the initial environmental indicators are called midpoints (Baumann and Tillman, 2004).

The Figure 4 below is an overview of the environmental impact indicators (midpoint) and their relationship between flow material data, and endpoint. For the aim of our study we focused only on the allocation of the material flow to the midpoint (dashed box).

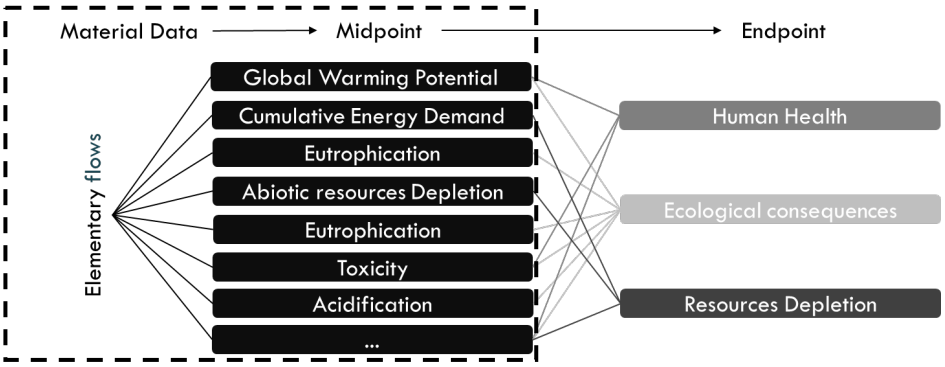

Figure 4 Example of combining midpoint indicators to elementary flows, and endpoints. The dashed box represents the combining of only the midpoint (environmental indicators) with the elementary flows, in order to select the relevant indicators during the first screening step.

The environmental indicators listed in Figure 4 are just a part of those selected on the basis of the material used and emitted from each process.

4 Results from the interviews with experts

4.1 Material flow data

Table 1 The table reports all the material flows used (input) or produced (output) from each process of the system.

Process	Technologies	Input	Output
DWW	AnMBR + FC	Electricity DWW Inoculum Propylene glycol	P-rich concentrate CO_2 CH_4 Effluent
	SBR - EBPR	Energy DWW NOx HCl NaOH	Effluent Sludge
Sludge treatment	Biodrying	Sludge Heat	Ash Other gases
	Incineration	Fuel Air CO_2	PM (Dust) NOx
	HTC	Energy Sludge H_2SO_4	CO_2 H_2 CH_4 CO Hydrochar HTC liquor
P recovery	Struvite precipitation	Energy P-rich concentrate, HTC Liquor or Ash Oxalic acid NaOH $MgCl_2$ H_3PO_4 Clinoptilolite	Cake FeC_2O_4 & CaC_2O_4 Struvite Effluent
	Dicalcium phosphate formation	Electricity Ash H_2SO_4 Water Calcium source ($CaO/Ca(OH)_2/CaCO_3$)	Gypsum Dicalcium phosphate CO_2
Farm	P rich product application	Sludge/Hydrochar/Struvite/ /Dicalcium phosphate Water	CH_4 N_2O

4.2 Actors

Table 2 Actors relevant to the development of each sector of the system and their process linkages.

Actors	DWWT & sludge treatment	P-recovery technologies	Agricultural activities
Environmental technology companies	✓	✓	✓
Researchers	✓	✓	✓
Dairy industry	✓		
Fertilizer industry		✓	
Wastewater treatment plant	✓		
Policy-makers		✓	
Farmers			✓

4.3 EU Policies

Table 3 List of EU polices relevant to the development of each sector of the system and their process linkages.

EU Policies	DWWT & sludge treatment	P-recovery technologies	Agricultural activities
The **Waste Framework Directive** sets the basic concepts and definitions related to waste management, including definitions of waste, recycling and recovery (https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en).	✓		
European chemical regulation concerns the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH). This regulations aims to ensure a high level of protection of human health and environment (https://ec.europa.eu/environment/chemicals/index_en.htm).		✓	
EU Fertilizing Product Regulation: From summer 2022 onwards, fertilizer producers, traders and farmers are confronted with the EU Fertilizing Products Regulation (FPR), which radically changes the way fertilizers are receiving the CE mark and the labelling requirements provided on the products. In the future, it is now possible to market, within the EU, a very wide range of fertilizing products such as organic fertilizers, organo-mineral fertilizers, growing media or biostimulants – provided that they comply with the environmental and safety requirements of the new legislation (https://www.fertilizerseurope.com/agriculture-environment/fertilizing-products-regulation/).			✓
The **Industrial Emissions Directive (IED)** and the Environmental Impact Assessment (EIA) Directive are two EU instruments that affect the decisions for all the processes of the system. The IED is the main policy regulating pollutant emissions from industrial technologies, by achieving a high level of protection of human health and environment throughout a better application of Best Available Techniques (BAT) (https://ec.europa.eu/environment/industry/stationary/ied/legislation.htm). In 2021 the Water Europe was invited to update the IED in order to be more focus on pollution reduction to water and soil and improve water efficiency (https://watereurope.eu/water-europe-new-position-paper-a-new-industrial-emissions-directive/).	✓	✓	✓
All the processes of the system are under the control of the **Environmental Impact Assessment Directive:** dairy industries, wastewater treatment plants, extraction of phosphate and intensive agricultural activities (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31985L0337&from=EN https://ec.europa.eu/environment/eia/eia-support.htm).	✓	✓	✓
Water Framework Directive: Water protection is therefore one of the priorities of the Commission. European Water Policy should get polluted waters clean again, and ensure clean waters are kept clean. The following will provide an overview on development, present state and future of European Water Policy (https://ec.europa.eu/environment/water/water-framework/info/intro_en.htm) (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000L0060-20141120).	✓		
Classification, Labelling and Packaging (CLP) Regulation is based on the United Nations' Globally Harmonised System (GHS) and its purpose is to ensure a high level of protection of health and the environment, as well as the free movement of substances, mixtures and articles throughout the label (https://echa.europa.eu/regulations/clp/understanding-clp) (https://europa.eu/youreurope/business/product-requirements/chemicals/classification-labelling-packaging/index_en.htm).		✓	
Common Agricultural Policy (CAP) is the agricultural policy of the European Union which implements a system of agricultural subsidies, such as farms or agricultural organizations, and other programs. The CAP supports farmers to improve agricultural productivity and apply environmentally friendly practices. At the same time, the European Union has implemented environmental policies to protect water resources and reduce the impacts of agriculture on the aquatic ecosystems (EU, 2020a).			✓

5 Selection criteria in reviewed documents

Table 4a Initial list of criteria for the evaluation and selection of sustainability indicators listed in the reviewed documents.

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)
Clear in value	The indicator should be able to demonstrate a move towards or away from sustainability; it should not be uncertain about which direction is good and which is bad.	✓	✓				✓		
Measurability	The indicator should be **accurate**, or rather, the closeness to the context of the system under analysis should be **measurable**; the indicator should also be **consistent over time**, and **robust** (be **able to withstand changes**).	✓	✓	✓	✓	✓	✓	✓	✓
Availability	The indicator should be **affordable**; in order to use this indicator, a frequency **and timeliness of available** data is needed.	✓	✓	✓	✓	✓	✓	✓	✓
Quality	The indicator should be **standard** enough for comparison between all the European regions, and it should be based on **scientific** data.	✓	✓	✓	✓		✓	✓	✓
EU Policy Responsiveness	This criterion refers to the relevance of the indicator for EU policies. The indicator is supplied for communicating evidence to policy processes.	✓		✓	✓			✓	✓
Geographical scopes	Indicators need to be allocated and matched to a specific **geographic area**, or rather Europe. The indicator should also provide a sufficient level of European cross-**country comparability**, as far as is practically possible, with the use of international data collection standards.		✓	✓	✓			✓	
Guiding	The indicator should provide information in time to act on it, and it should be able to guide future actions.	✓		✓	✓				
Adaptable & Representativeness	The indicator is adaptable and applicable to a broad range of systems of different sizes and types. The dynamic of the indicators should reflect more than the dynamics of the specific time and place where the data was collected from.	✓	✓		✓	✓	✓		✓
Participatory	The indicator should be accessible to users, and easy to understand and use for decision making, and have a sensitive capability. The indicator should make use of what people can measure for themselves.	✓		✓	✓	✓	✓		✓
Democratic	People should have input on which indicator to choose and have access to results.	✓							

Table 4b Initial list of criteria for the evaluation and selection of sustainability indicators listed in the reviewed documents.

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)
Compelling	Interesting, exciting, suggestive of effective action	✓	✓						
Relevant	The indicator should be appropriate to the context, or system which it intends to indicate, and be able to provide an early warning of the potential problem.		✓	✓	✓	✓	✓	✓	✓
Supplementary	The indicator should include what the people cannot measure for themselves	✓							
Hierarchical	A user can delve down to details if desired but can also get the general message quicky	✓							
Physical	It best wherever possible to measure it in physical units	✓							
Tentative	Up for discussion, learning, and change	✓							
Attractiveness to Media	The indicator evaluates the media interest with the particular indicator.			✓					
Predictivity	No definition was provided by the author				✓				
Effectiveness	No definition was provided by the author				✓				
Responsiveness	No definition was provided by the author				✓				
Comparability	Indicators are the same, or compatible with other indicator systems.				✓		✓		
Theoretical basis	The consistency of an indicator with ecological theory, but also the degree to which diverse professionals all accept the theoretical arguments.					✓			
Domain	Coverage of a range of domains that can be influenced by the plan						✓		

6 Affiliations of the participating actors

During the conference, different actors participated and 18 responded to the survey. Figure 5 below reports their general affiliations. The majority of the actors who answered the questionnaire work in academia (53%) and in companies (26%), the rest are from research institutes and governmental offices. Although the group of participants does not cover all relevant actors, these are some of the primary actors in many decision contexts relevant for phosphorus recovery, dairy wastewater treatment and fertiliser use.

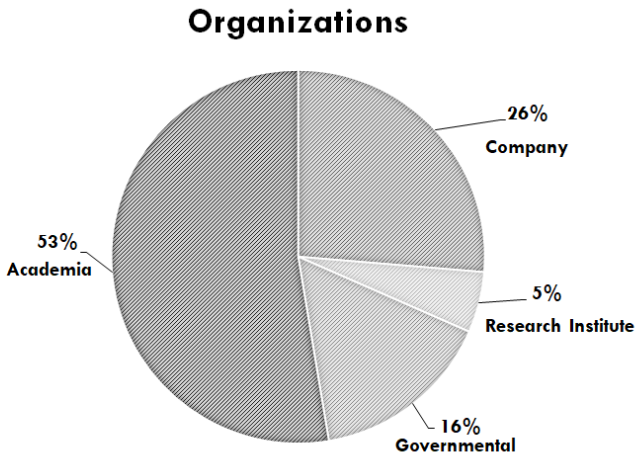

Figure 5 Results of the proportion of the organization where the actors responded to the survey works.

For more details about the results of the questionnaire please see SM2.

7 References

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guid to LCA - An orientation in life cycle assessment methodology and application.

EC, 2001. GUIDING PRINCIPLES FOR THE SELECTION OF INDICATORS AND STATISTICS, in: Committee, S.P. (Ed.).

Judd, S., 2022. Incineration of sludge. https://www.sludgeprocessing.com/oxidative-thermochemical-treatment/incineration-sludge/. (Accessed December 2022).

Latruffe, L., Diazabakana, A., Bockstaller, C., Desjeux, Y., Finn, J., Kelly, E., Ryan, M., Uthes, S., 2016. Measurement of sustainability in agriculture: a review of indicators. Studies in Agricultural Economics 118, 123-130.

Lebacq, T., Baret, P.V., Stilmant, D., 2013. Sustainability indicators for livestock farming. A review. Agronomy for Sustainable Development 33(2), 311-327.

Lundin, M., Molander, S., Morrison, G., 1999. A set of indicators for the assessment of temporal variations in the sustainability of sanitary systems. Water Science and Technology 39, 235-242.

Mascarenhas, A., Nunes, L.M., Ramos, T.B., 2015. Selection of sustainability indicators for planning: combining stakeholders' participation and data reduction techniques. Journal of Cleaner Production 92, 295-307.

Nathan, H.S.K., Reddy, B.S., 2010. Selection criteria for sustainable development indicators. Mumbai: Indira Gandhi Institute of Development Research.

Numviyimana, C., Warchoł, J., Izydorczyk, G., Baśladyńska, S., Chojnacka, K., 2020. Struvite production from dairy processing wastewater: Optimizing reaction conditions and effects of foreign ions through multi-response experimental models. Journal of the Taiwan Institute of Chemical Engineers 117, 182-189.

Numviyimana, C., Warchoł, J., Ligas, B., Chojnacka, K., 2021. Nutrients Recovery from Dairy Wastewater by Struvite Precipitation Combined with Ammonium Sorption on Clinoptilolite. Materials (Basel, Switzerland) 14(19), 5822.

Prayon, 2022. DCP Feed - GetMoreP. https://www.prayon.com/en/processes/DCP-getmoreP/.

Revi, A., 1998. Indicators and information systems for sustainable development.

Reza, M.T., Wirth, B., Lüder, U., Werner, M., 2014. Behavior of selected hydrolyzed and dehydrated products during hydrothermal carbonization of biomass. Bioresour Technol 169, 352-361.

Roy, R., Chan, N.W., 2012. An assessment of agricultural sustainability indicators in Bangladesh: review and synthesis. The Environmentalist 32(1), 99-110.

Supplementary material 2 - Sustainability indicator identification and selection for an innovative conceptual system: phosphorus recovery from dairy wastewater

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A meta-analysis of LCAs for environmental assessment of a conceptual system: Phosphorus recovery from dairy wastewater

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ABSTRACT

A significant increase in phosphorus-rich dairy wastewater coincides with a decrease in the availability of fossil phosphate rock resources in Europe. This confluence of events has led to the development of technologies for phosphorus recovery from dairy wastewater. This study aims to inform and guide such development with regard to life cycle environmental impacts prior to their implementation in dairy contexts. With the lack of inventory data at this point and the non-existence of earlier life cycle assessments on the use of phosphorus recovery technologies in a dairy context in literature, we performed a meta-analysis where we extracted and compared published results on life cycle environmental impacts from two fields (1) dairy industries, with a focus on the dairy wastewater treatment and (2) phosphorus recovery technologies in a municipal wastewater treatment context. The results show that despite its intended effect, normal dairy wastewater treatment in many cases still contributes significantly to eutrophication. Most of the phosphorus recovery technologies examined here exhibited a lower global warming potential and cumulative energy demand than those of dairy wastewater treatment processes. It indicates that problem shifting could be avoided when phosphorus recovery is introduced. However, no technologies involving incineration have had the impact of acidification reported which represents a potential knowledge gap since impacts are expected related to incineration emissions. A comparison between the extracted data for phosphorus recovery technologies shows that there are lower impacts related to technologies that recover phosphorus from the liquid phase, than from sludge or ash.

1. Introduction

European food security is threatened by Europe's lack of phosphate reserves and by sources of phosphate rock being located in geopolitically sensitive regions (Schröder et al., 2010). Phosphate rock is a finite, non-renewable resource that is mostly used in fertiliser production. Fertiliser demand is expected to increase owing to a growing world population and consequent increase in demand for food. From 1983 to 2013, the global consumption of phosphate rock increased by 25% (Bradford-Hartke et al., 2015). The increasing demand for this finite resource led the European Commission to declare phosphate rock as a critical raw material in 2014, and phosphorus (P) as a critical element in 2017 (European Commission, 2017). Therefore, an alternative to using phosphate rock for fertiliser production is required.

To respond to this challenge, the European Union (EU) has prioritised the recovery and safe reuse of P from food and municipal waste flows through its circular economy package (European Commission, 2016). Therefore, interest in development of technologies with regard to nutrient recovery from organic waste streams has increased in recent years. A potential input waste stream for these technologies is dairy wastewater (DWW).

According to the European Dairy Association (EDA), the dairy sector is the most economically important part of the European agri-food industry, and it is present in all EU member states. It provides nutrition to all generations of the European population and regular earnings to 300.000 employees in dairy companies as well as the connected 700.000 farmers producing raw milk (EDA, 2018). The total EU milk production is approximately 160 million tons (22% of the world's total milk production) (EDA, 2018). The EU is a major exporter of dairy products and the largest cheese and skimmed milk powder exporter in the world (EDA, 2018). The European milk quota system was introduced in 1984 to limit public expenditure on the sector, control milk production, and stabilise milk prices and the agricultural income of milk producers (European Commission, 2009). After the system was abolished in 2015, the dairy sector grew (Slavov, 2017) and higher DWW volumes now need to be treated to avoid environmental problems (Ashekuzzaman

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et al., 2019). DWW is also a potential source (Yapıcıoğlu and Yeşilnacar, 2020) of P that could contribute to addressing the growing demand for fertilisers for food production. Because the dairy industry produces different products, the characteristics of DWW effluents also vary greatly, but the P concentration is typically higher in DWW than in municipal wastewater (Shilpi et al., 2018). The concentration of total P (TP) in DWW has been reported to vary from 8 to 280 mg/L (Demirel et al., 2005), and sludge produced from DWW treatment has been reported to have a content as high as 52 g TP/kg of sludge (Numviyimana et al., 2022).

To achieve the goal of P recovery in the dairy industry, the REFLOW European Training Network (ETN) has focused on developing and demonstrating processes for the recovery and use of P fertiliser products from DWW. The REFLOW ETN (January 2019–December 2022) has finances for 13 early stage researchers to investigate P recycling from dairy wastewater. The majority focus on technical aspects of P recovery, providing data to others that assess economic and environmental aspects.

The technical elements studied by REFLOW are: (i) accumulation, and crystallisation or mineralisation of P-rich products (struvite or phosphoric acid) from liquid effluents; (ii) drying or hydrothermal carbonisation of sludge; and (iii) extraction of heavy metal-free, water-soluble phosphate salts and phosphoric acid from ash from sludge incineration, in all cases to allow for the production of new fertilisers and enable more circular P flows through society. The work described in this study aims to explore the environmental challenges and opportunities associated with these types of P recovery from DWW.

A common method for assessing the environmental impacts of new technologies is life cycle assessment (LCA). LCAs have been used to assess the environmental impacts associated with dairy production and P recovery from different wastewaters, but no LCA study that combines the two has been reported. Furthermore, it is still too early to create an original LCA using data from the REFLOW ETN. Therefore, information from previous studies was extracted and compared in this study to identify potential environmental challenges and opportunities and thereby provide knowledge and guidance during early stages of technology development. To provide input to both technical development activities and to further environmental assessment efforts in the REFLOW ETN, the following two guiding questions were formulated: (1) Are the environmental impacts related to dairy wastewater treatment (DWWT) an important part of the environmental impact of dairies, and what are the hot spots and influencing factors? and (2) What are the environmental impacts related to P recovery technologies in comparison to those of DWWT, and what are the influencing factors?

Owing to a lack of published LCAs on P recovery from DWWTs, an innovative approach for extracting and recalculating literature results (here called meta-analysis) was employed to compare results from LCA studies of dairy products to results from LCA studies of P recovery technologies made for other contexts. Thus, a novel combination of information from earlier LCA studies was compiled and assembled to generate new information that is useful for understanding the impacts of a combined system that represents P recovery in a dairy context.

2. Materials and method

In this study, LCA results from two different industrial contexts were explored, extracted and compared: (1) the dairy industry, particularly its wastewater treatment, and (2) P recovery technologies (typically applied to municipal wastewater treatment), with the aim of understanding its application in the dairy industry. This required careful data extraction and recalculation of some information to allow for conclusions to be drawn regarding the environmental challenges and opportunities of a combined system. This section describes the methodology that was applied to shed light on the environmental impacts related to DWWT, P recovery technologies, and combined systems. Firstly, the technical context as defined by the needs of REFLOW is described. As no LCA studies exist that focus on P recovery in a dairy context, LCA studies on dairy operations that include details on DWWT were explored in a first step and then LCA studies on P recovery. Finally, information from both were compared to provide an understanding for the challenges and opportunities of a combined system. For this comparison, assumptions based on additional quantitative information regarding both the P content in DWW and the efficiency of studied P recovery technologies had to be made to connect information from the two groups of LCA studies.

2.1. General description of the investigated system

Because of the intended focus on P recovery from the dairy industry in this study, the major interest was its current generation and treatment of DWW. The sizes of dairy processing plants and the types of manufactured products vary significantly between sites. Generally, dairy plants can be divided into different production sections, and each section produces wastewater (Costea and Ghinea, 2021). In terms of volume and composition, DWW depends on the type of products generated and specific processes used in the dairy industry (Brazzale et al., 2019). The treatment of DWW normally consists of three steps (see Fig. 1). The first process removes fats, oils, and grease through dissolved air flotation (DAF); the second is an anaerobic and/or aerobic treatment; and the third is focused on the removal of nutrients through chemical or biological treatment (Ashekuzzaman et al., 2019; Brazzale et al., 2019).

P recovery from dairy wastewater is innovative, and no LCA currently exists that describes the environmental impacts of such a system, but comparable contexts can be found in municipal wastewater treatment plants. There are many different possibilities for nutrient recovery from wastewater (reviewed, e.g., in Harder et al. (2019)), and an increasing number of recovery processes have been implemented specifically for P recovery (an overview is provided in Egle et al., 2015). P recovery can be performed either from the liquid phase, sludge, or ashes generated from the incineration of sludge (please see chapter 2 of the supplementary material (SM) for further details on the P recovery technologies). The main P-containing product recovered from the liquid phase is struvite (magnesium ammonium phosphate). In these processes, after sludge thickening and dewatering, the liquid phase is subjected to crystallisation or precipitation, which is controlled by a combination of precipitation agents ($Cl_2H_{12}MgO_6$ and NaOH) and pH control (Linderholm et al., 2012). With regard to recovery from sludge, in municipal wastewater treatment contexts, it is common to first digest sludge for stabilisation and biogas production. For digested sludge, various P recovery approaches have been developed, ranging from direct application on agricultural land to recovery from sludge, such as wet chemical approaches (Egle et al., 2015). The recovery of P from ash after incineration can be achieved through wet chemical, thermo-chemical, or thermo-electric approaches (Egle et al., 2015). Each technology has a different P recovery potential which depends on both the technology employed and its initial source. Fig. 1 shows a conceptual system with P recovery from DWW, showing optional P recovery routes implemented in the context of DWWT.

2.2. Compiling earlier studies

The literature review for various parts of the study was completed in May 2021 using Scopus and Web of Science services. Documents were extracted based on the title, keywords, and abstracts. Relevant publications from any prior point in time were searched, and no filter for the year of publication was employed. Search terms are provided in the SM section 1. Studies which focused only on raw milk production on the farm in the assessment were excluded after an initial review. Studies that focused on the cleaning in place (CIP) process were also excluded. The CIP process is a procedure that allows the cleaning and sanitisation of dairy equipment without disassembling it or disconnecting the pipes (Gabrić et al., 2016). Wastewater from CIP is very low in nutrients, so it

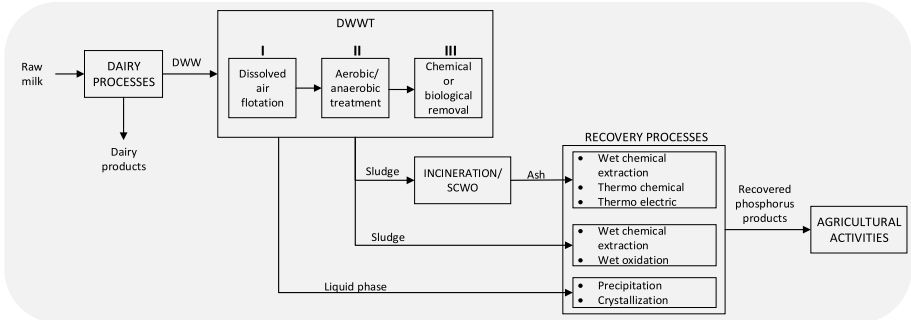


Fig. 1. Representation of a possible system with recovery of phosphorus from dairy wastewater, showing the optional recovery from liquid, sludge, or ash; a few example technologies are listed. DWW = Dairy wastewater. DWWT = Dairy wastewater treatment. SCWO = Super critical water oxidation.

was not the type of flow considered in REFLOW, and wastewater treatment was also not assessed in these studies. For P recovery, studies were included only if they focused on technologies employed to recover P (and sometimes also other nutrients), but not if they focused only on the removal of nutrients and/or reuse of the 'cleaned' water. Furthermore, REFLOW does not consider the direct application of sludge or ash in the field; therefore, such studies were excluded. Some EU member states are hesitant to allow the application of sludge directly on land because of concerns regarding the possible presence of heavy metals, pathogens, pharmaceuticals, and complex organic compounds that can contaminate soil. P in ash is also insoluble in water and has low plant availability (Egle et al., 2015). After the first literature screening and initial sorting, 25 studies remained that dealt with LCA of dairy industries (23 LCAs of dairy product manufacturing and two LCAs of DWWT), and nine studies dealt with LCA of P recovery technologies.

Since the review of LCAs of dairy activities aimed primarily at revealing the potential environmental impacts of DWWT, a second sorting revealed that only 17 of the 23 articles on the dairy industry actually included DWWT in the system boundary, and only nine of those presented life cycle impact assessment (LCIA) results for DWWT explicitly (see Fig. 2). Regarding LCA studies on P recovery technologies, only six of the nine articles allowed for the extraction of environmental impact data for the recovery process only (see Fig. 2).

In addition, to allow for the integration of the two sets of studies into an understanding of impacts for the combined system described in Fig. 1, one paper with an overview and description of technologies for recovering P and seven on the chemical characteristics of dairy industry wastewater were consulted (see Fig. 2).

Since the purpose of this study was specifically to model systems not currently in operation, we had to be particularly selective regarding the available literature. Few studies report sufficiently disaggregated data of the right kind on the right topics. Nevertheless, with the literature that survived our review criteria we were able to cover a wide range of dairy processing and P-recovery systems.

2.3. Meta-analysis (collecting, recalculating, and assembling)

When extracting environmental impact results from published LCA studies, it must be remembered that the results are not directly comparable due to differences in functional units (FUs), environmental impact categories, system boundaries, and type of inventory data used. Therefore, the specifics of each included study must be carefully considered. A process similar to that suggested by Hermansson et al. (2019), called a meta-analysis of LCAs, was followed.

First, data from different studies were extracted and restructured. Fig. 3 shows the system parts that we wanted to extract information for from what was generally the full scope of the reviewed studies. To answer the first research question, impacts related to the dairy processes but separated for DWWT (gate-to-gate in the upper part of Fig. 3) and other parts were needed; in order to answer the second research question, impacts related to P-recovery processes as such (gate-to-gate in the lower part of Fig. 3) were needed. Incineration (and in one case, supercritical water oxidation) was considered part of the P recovery gate-to-gate system, when possible, as it was expected to bring a considerable environmental impact if installed for a DWW context; we point this out specifically, as this part was excluded in some LCA studies in the

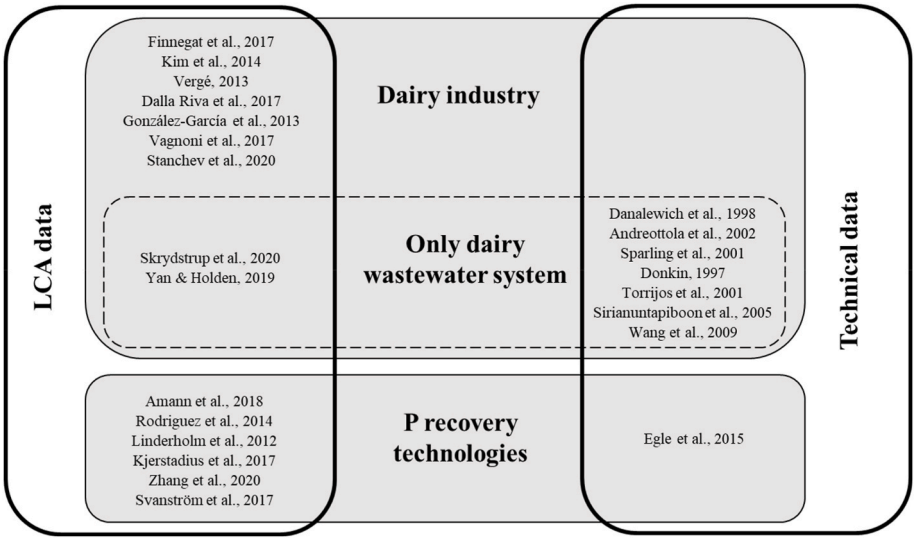


Fig. 2. Diagram illustrating the number and type of articles ultimately selected and reviewed for this paper.

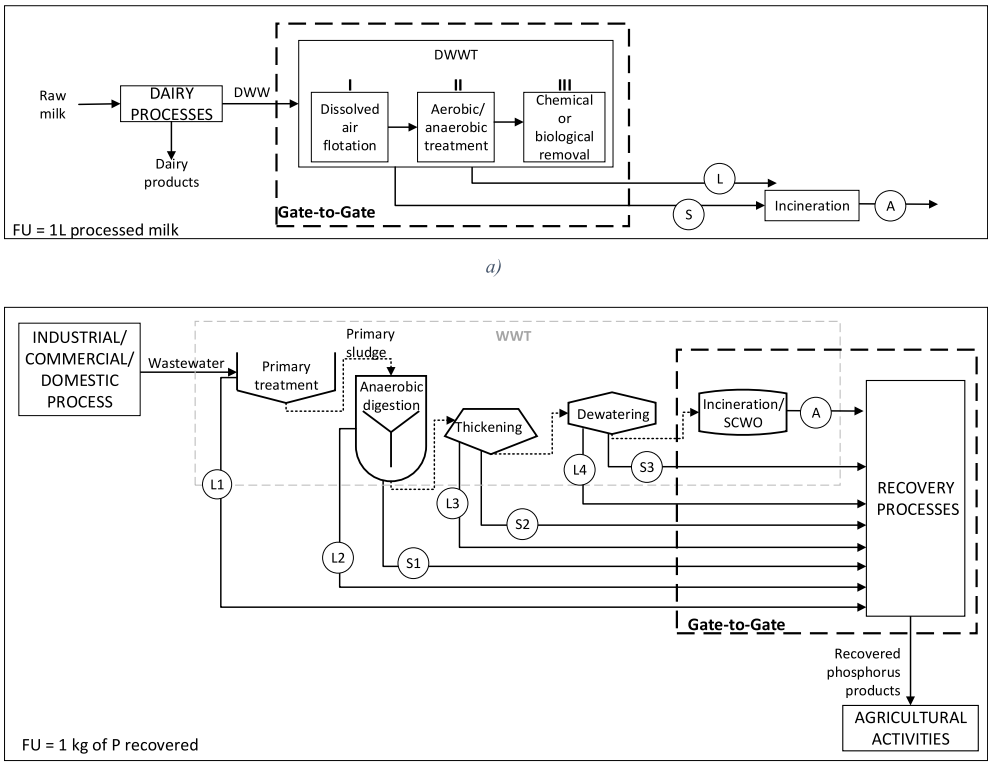


Fig. 3. System boundaries for the reviewed studies and for the system parts that were extracted for the comparison in the present study marked with bold dashed boxes for (a) the dairy wastewater treatment (DWWT) and (b) the P recovery process. A comparison was also made between the DWWT and the rest of the dairy process in (a). DWW = dairy wastewater; FU = functional unit; WWT = wastewater treatment. The letters represent liquid flow (L), sludge (S), and ash (A) obtained from different processes of the WWT and used in the recovery processes; the numbers added in (b) show the different extraction points considered in the reviewed studies and are referred to in Table 2.

literature. For other technologies, all the unit processes that would bring a considerable environmental impact if they were installed for DWW had been included. Data related to dairy farms, retailing, use and disposal of final products, municipal wastewater treatment, and any by-product system expansion were carefully removed. Nevertheless, some potentially important gaps and overlaps were present, which may have influenced the comparison. More specifically, neither of the technologies described by Amann et al. (2018) included the incineration operation and the struvite crystallisation process described by Zhang et al. (2020) included anaerobic digestion (AD) at the municipal wastewater treatment (WWT) plant.

Second, the information on environmental impacts was rescaled to the same FU. In LCAs on dairy products, it is common and recommended by the International Dairy Federation (IDF) (FIL-IDF, 2015) to use an FU of 1 kg of product. However, since the present study intended to find the total impact from dairy operations, as well as the share related to DWWT, in the first step, impacts were instead related to 1 L of processed milk (see the upper system in Fig. 3). One option could have been to relate the impacts directly to the flow of a unit of DWW, as it would be more relevant for the combined system later on, but as the amount of DWW per kg of product and per L of processed milk varies depending on specific practices that are not in focus in our study, we found it more relevant to base the first part of the analysis on the input of milk (FU = 1 L of processed milk).

According to the literature on LCA of P recovery technologies, 1 kg of P recovered is a common FU (see the lower part of Fig. 3). Together with the fact that this study is intended to be used in the development of P recovery technologies in a dairy context, 1 kg of recovered P was therefore used as a FU in the final compilation of the results of this study. To answer the second research question, the impact of the DWWT as gathered from the dairy LCAs was recalculated to relate to the P in the DWW. For this, further data were collected and analysed. These were the typical DWW volumes (scaled to 1 L of processed milk, collected from the LCAs in the dairy industry; see Table 13 in the SM) and the typical P concentration of DWW (from seven studies on DWW characteristics; see Table 14 in the SM). As the published LCA studies lacked sufficient detail to allow for targeted selection, the average value of the P concentration in DWW was calculated after exclusion of extreme values (10 mg/L, and 640 mg/L); the average of the 20 remaining values was 67 mg/L. Also, we did not want the results to be scaled for a particular situation but for an average situation.

Finally, to relate the extracted and rescaled environmental impact results of the DWWT process to those of the P recovery process in a conceptual combined system (as represented in Fig. 1), further data on the efficiency of different P recovery technologies were collected and analysed (from the overview by Egle et al. (2015)).

By setting the concentration of P in the DWW to an average number the P flow in the DWW for the dairy LCA studies could be calculated (see Table 16 in the SM) and knowing the P recovery potential for different types of technologies made it possible to calculate the typical DWW volume needed for recovery of 1 kg of P (see SM section 4 for further details about the calculations). Finally, it was possible to relate the environmental impact of the DWWT to the environmental impact of P recovery for the same flow of P.

When evaluating the available information in the reviewed LCA studies, it was observed that only a few environmental impact categories were common to several studies and could be used in the final comparative work: cumulative energy demand (CED), climate impact based on global warming potential (GWP), and acidification based on acidification potential (AP). It would have been interesting to look into more categories, but these are the only ones that the available material allows.

3. Results and discussion

3.1. Dairy industry process

Table 1 presents a selection of LCIA results from the nine studies that eventually provided recalculated LCA results for dairy products (seven LCAs of dairy product manufacturing and two LCAs of DWWT), scaled to

Table 1
LCIA data for only the dairy wastewater treatment (DWWT) process, extracted from earlier LCAs and recalculated. These data are here scaled to the FU of 1 L of processed milk. The second column shows which of the dairy factories assessed in the LCA studies includes the DWWT on-site. The reported percentage values represent the contribution of the dairy wastewater treatment to the impact of the whole dairy. The environmental impact categories shown are climate impact based on global warming potential (GWP), cumulative energy demand (CED), eutrophication impact based on either freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), or eutrophication potential (EP), acidification impact based on acidification potential (AP), and water depletion (WD) with units as provided in the first row of the table. Note that methods from several different LCIA frameworks are represented here (see SM section 7). The last two studies focused only on the DWW management. More details for all studies are found in the SM, e.g. section 3.1.

Studies	DWWT on-site	Products	GWP (kg CO_2 eq)		CED (MJ)		FEP (kg P eq)		MEP (kg N eq)		EP (kg PO_4^{-3}eq)		AP (kg SO_2 eq)		WD (m^3)	
González-García et al. (2013)		San Simon	2.73×10^{-2}	16%	2.55×10^{-1}	11%					5.45×10^{-4}	75%	1.82×10^{-4}	17%		
Kim et al. (2013)	✓	Cheddar	6.09×10^{-3}	4%	4.36×10^{-2}	2%	7.27×10^{-5}	61%	1.85×10^{-3}	96%					7.92×10^{-5}	2%
		Mozzarella	8.28×10^{-3}	3%	4.97×10^{-2}	2%	9.98×10^{-5}	48%	2.09×10^{-3}	95%					1.81×10^{-4}	1%
Dalla-Riva et al. (2017)	✓	Mozzarella	9.55×10^{-4}	1%	8.35×10^{-3}	1%	1.59×10^{-6}	18%	4.65×10^{-5}	23%			6.31×10^{-6}	4%	1.14×10^{-3}	34%
Vagnoni et al. (2017)		Pecorino									3.02×10^{-3}	1%				
Finnegan et al. (2017)	✓	Butter	5.71×10^{-3}	6%	5.42×10^{-2}	7%	1.70×10^{-6}	16%	9.62×10^{-6}	62%			2.34×10^{-5}	10%	1.57×10^{-2}	15%
		Milk Powder	6.88×10^{-3}	3%	6.73×10^{-2}	3%	1.80×10^{-6}	13%	1.20×10^{-5}	48%			3.62×10^{-5}	5%	1.72×10^{-2}	13%
Vergé et al. (2013)		Fluid Milk	8.21×10^{-4}	2%												
		Yoghurt	1.70×10^{-3}	1%												
Stanchev et al. (2020)		–	8.36×10^{-3}	8%			1.54×10^{-3}	6%							1.84×10^{-4}	16%
Skrydstrup et al. (2020)		–	3.03×10^{-3}	[a]	4.56×10^{-3}	[a]										
Yan and Holden (2019)	✓	Butter A									9.43×10^{-4}	[a]				
		Butter B									5.21×10^{-4}	[a]				

[a] The share of the total could not be calculated because the total was missing.

the FU of 1 L of processed milk. Different LCIA frameworks are represented depending on the choices made in the individual studies; in particular, different types of methods for assessing eutrophication impact were employed (see SM section 7).

As can be seen from Table 1, the LCIA results for DWWT vary greatly between studies, but mostly within one to two orders of magnitude, depending on the impact category. The percentage numbers provided in Table 1 show the share of the total environmental impacts of dairy operations that the WWT processes make up. Clearly, DWWT in many cases makes up a significant part of the dairy industry's environmental impact, but the range is large: from 1 to 96% for different studies, dairy products, and impact categories. The results show that the DWWT (which includes the impact of the release of the treated water) contributes particularly to the eutrophication impacts of the dairies, but also to water depletion (WD); between different studies, the largest variation in the DWWT share is for the eutrophication impacts. Emissions associated with DWWT contribute approximately 6–62% and 23–96% to the total freshwater and total marine eutrophication impacts, respectively. For the three indicators that are used in the comparison to the impact of P recovery technologies in the next section of this paper (CED, climate impact, and acidification), the DWWT's contribution to the overall impact on dairy production is never larger than 17% in the analysed studies (please to see section 3.1 of the SM for more details on the calculations).

It must be remembered that the main point of performing DWWT is generally to reduce (or fulfil legal obligations aimed at limiting) the eutrophication impact. Even with DWWT, this impact is still important according to the reviewed studies, and it is dominated by the discharge of nutrients in the effluents and influenced by various processes in the dairy industry. The nutrients in wastewater originate from losses of both raw milk and dairy products (Dalla-Riva et al., 2017), but also from detergents used in the cleaning process (Eide, 2002). Another important factor which influences the eutrophication impact is dairy size (Stanchev et al., 2020). DWW can be transported to a WWT plant in a local municipality or treated on-site. On-site DWWT plants, which seem to contribute considerably to freshwater and marine eutrophication, as reported in more than one study (Dalla-Riva et al., 2017; Kim et al., 2013; Yan and Holden, 2019), are typical of small-scale mills. This type of mill typically does not produce a volume of whey that makes it profitable to install specific equipment for whey processing for secondary purposes, such as protein powder production. Therefore, the whey stream produced is often mixed with DWW effluent, increasing the

Table 2
Overview of P recovery technologies considered in the selected LCA studies, and the short names used in this paper (T1-22). P is recovered from three different source flows listed in the second column; see Fig. 3 for their origin in the WWT. Typical P concentrations in the considered flows are shown with the estimated P yield (recovery potential) as provided in Egle et al. (2015). The recovery potential is relative to the content in the original wastewater. The studies highlighted in grey are those which have an overlap (dark grey) or a gap (lighter grey) in the environmental impact data with regard to the gate-to-gate boundaries shown in Fig. 3b. The table also reports the P product and its common name in parenthesis. AD = Anaerobic digestion process; SCP = Struvite Crystallisation Process; WAO = Wet air oxidation; SCWO = Super critical water oxidation; TS = total solids.

Name in reviewed study (reference)		Source flow	P concentration (in the source flow in the reviewed study)	Recovery method(s)	Obtained product	P recovery potential (Egle et al., 2015)
T1	REM-NUT (Amann et al., 2018)	L1	~ 5 - 10 mg PO_4-P/L	Ion-exchange; Precipitation	Magnesium ammonium phosphate (Struvite)	~ 50% - 70%
T2	AirPrex® (Amann et al., 2018)	L2	Dissolved part: 20 – 400 mg PO_4-P/L	Crystallization		~ 10% - 15%
T3	P-RoC (Amann et al., 2018)	L3 – L4			Calcium phosphate	10% - 25%
T4	Ostara Pearl® (Amann et al., 2018)				Magnesium ammonium phosphate (Struvite)	
T5	Ostara Pearl® (Linderholm et al., 2012)					
T6	Struvite precipitation (Kjerstadius et al., 2017)	L2		Precipitation		~ 10% - 15%
T7	Crystallization (Zhang et al., 2020)			AD + Crystallization		40%*
T8	SCP (Rodriguez-Garcia et al., 2014)			Crystallization		35%*
T9	Wet chemical - Stuttgart (Amann et al., 2018)	S2	~ 1.4 g P/kg of sludge	Wet chemical extraction		~ 45%
T10	Wet chemical - Gifhorn (Amann et al., 2018)					
T11	PHOXNAN (Amann et al., 2018)	S3 – S4		Wet chemical extraction + WAO		~ 50%
T12	Aqua Reci® (Amann et al., 2018)	A	~ 50 - 130 g P/kg TS	SCWO + Precipitation	Calcium phosphate	~ 70%
T13	ICL Fertilizers® (Amann et al., 2018)			Wet chemical extraction (with H_2SO_4)	Single super phosphate (SSP)	~ 85%
T14	RecoPhos® (Amann et al., 2018)			Wet chemical extraction (with H_3PO_4)	Triple super phosphate (TSP)	
T15	EcoPhos® (Amann et al., 2018)			Acid wet chemical leaching	Phosphoric acid	~ 80%
				(Multi modular decontamination)		
T16	PASCH (Amann et al., 2018)			Acid wet chemical leaching (solvent extraction)	Calcium phosphate	~ 70%
T17	LEACHPHOS® (Amann et al., 2018)			Acid wet chemical leaching		~ 60 - 70%
T18	Ash Dec® (Cold Ash) (Amann et al., 2018)			Thermo-chemical	Depolluted ash	~ 85%
T19	Ash Dec® (Hot Ash) (Amann et al., 2018)					
T20	Ash Dec® (Linderholm et al., 2012)			Incineration + Thermo-chemical		
T21	Ash Dec® (Svanström et al., 2017)					
T22	Thermphos® (Amann et al., 2018)			Thermo-electric	Tetra phosphorus	~ 83%

*These sources were extracted from LCA studies (Zhang et al. (2020); Rodriguez-Garcia et al. (2014)).

nutrient concentration in the flow sent to an on-site treatment plant (González-García et al., 2013). Furthermore, P emissions contribute to a higher eutrophication impact due to the digestion of wastewater from whey processing (Kim et al., 2013). On-site treatment demands additional energy for the WWT plant, and energy production therefore also contributes indirectly to increases in different environmental impacts in those cases (Yan and Holden, 2019).

In a study by Stanchev et al. (2020), in addition to requiring a large share of electricity (approximately 48% of electricity used in dairy industry), DWWT contributed strongly to WD (approximately 64%) because of the production process for flocculants (in the specific case: calcium carbonate and sodium hydroxide).

The "yellow" products, such as cheese and butter, typically use more milk input per kg of product and therefore also produce a higher volume of DWW from the milk itself per kg of product compared to the "white" products, like fluid milk and yoghurt (European Commission, 2006, 2019). As Djekic et al. (2014) point out, this often leads to a higher impact per kilogram for yellow products than for white products. However, as the results are shown per litre of milk input in the present article, this effect cannot be seen here.

The fact that the eutrophication impact of the dairy is dominated by the content in the effluent, even as DWWT is present, reflects the fact that the treated DWW is still rich in nutrients which can possibly be recovered through the application of a recovery system. This could lead to a further reduction in the eutrophication impact and simultaneously generate valuable resources (although, the release of nutrients might primarily be governed by discharge permits). This makes it interesting to look at how large an impact that a typical P recovery process would bring, which would either be added to or would partially replace the impact from DWWT in a combined system. However, this comparison can, in this study, only be made for impact categories other than eutrophication for reasons described earlier.

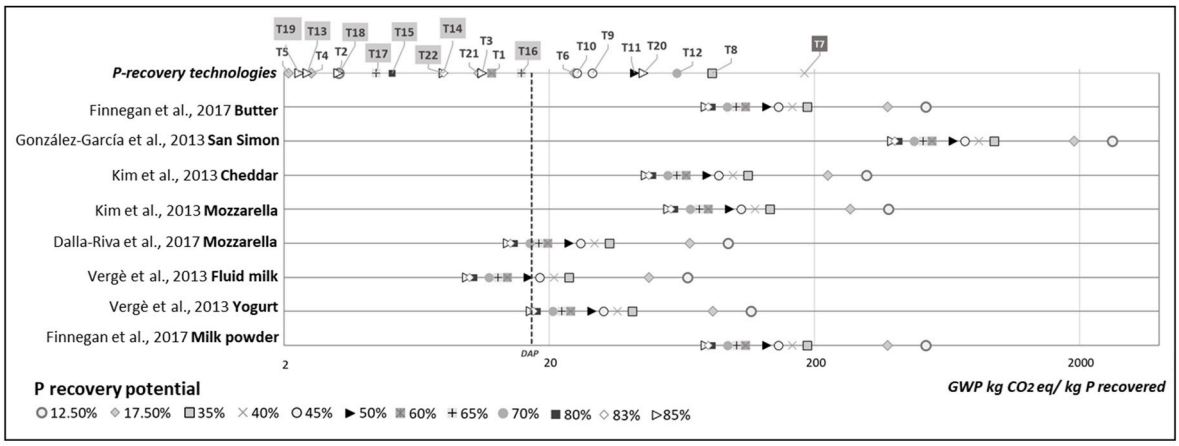
3.2. Comparison between P recovery technologies and DWWT

The second part of this study focused on the environmental impacts of P recovery technologies and the factors that influence them. The environmental impacts were also compared with those of DWWT. This information reveals if there would be large environmental challenges related to adding P recovery to existing DWWTs and it may shed light on what needs to be considered in the development and implementation process.

Table 2 presents a brief technical description of the P-recovery technologies considered in the selected LCA studies. P recovery was done in municipal WWT contexts, which is different from the dairy contexts in focus in this study. The technologies were thus applied to flows that differed in terms of P concentration and physicochemical characteristics (see Fig. 3b for the origin of the source flows) and had different P recovery potentials and generated different types of P products.

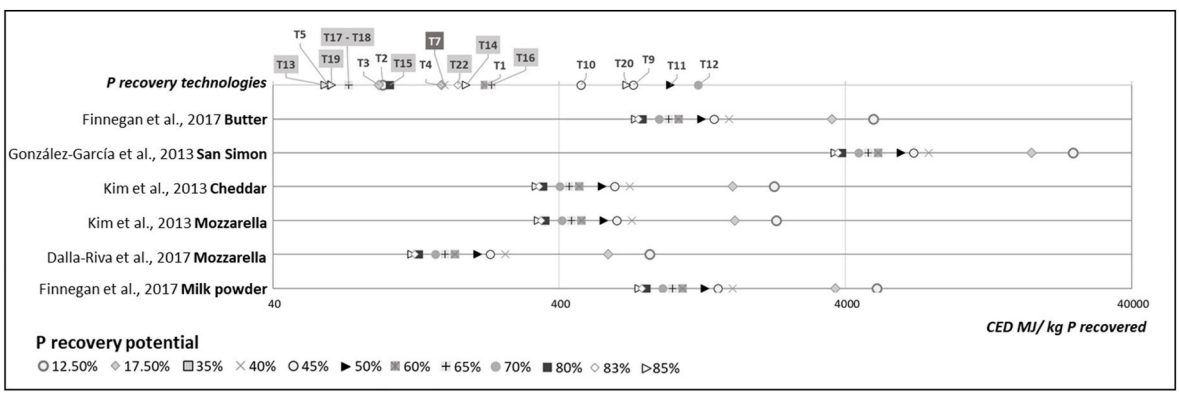
Fig. 4 shows the LCIA results related to the P recovery technologies for 1 kg of P recovered (top line in each chart) and compares them to the DWWT (all other lines in each chart) for the three environmental impact categories that allowed cross-comparisons between the two sets of LCA studies: CED, climate impact, and acidification. The same marker is used for all technologies with the same P recovery potential and may, therefore, appear more than once in the first line. The impact of an eventual P recovery process implemented in a dairy context can be estimated as the sum of two values: the value for the P recovery in the uppermost line and the value for the same marker in any of the other lines. However, it is likely that in a real case, either the DWWT or the P recovery needs to be modified in a combined process which may lead to lower or higher impacts than this sum.

In general, looking at the P recovery in all three charts in Fig. 4, it seems that gaps and overlaps in gate-to-gate system boundaries *vis-à-vis* the WWT gate-to-gate may influence the results (technologies marked with grey cells in Table 2). Most technologies which recover P from ash



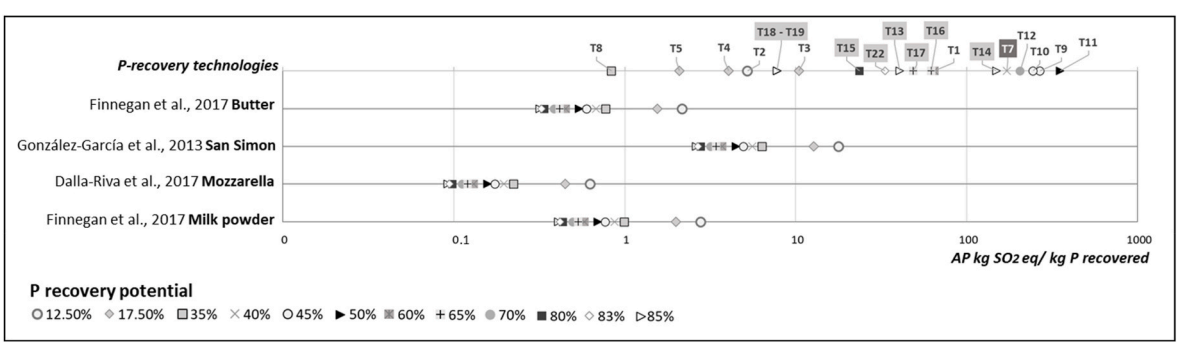
a)

Fig. 4a. Climate impact as global warming potential (GWP), for P recovery (top line for each chart) and for DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). The dark dashed line (4a) represents the climate impact per kg of P in DAP (Zhang et al., 2017). Note the logarithmic scale.



b)

Fig. 4b. Energy use as cumulative energy demand (CED) for P recovery (top line for each chart) and for DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). Note the logarithmic scale.



c)

Fig. 4c. Acidification impact as acidification potential (AP) for P recovery (top line for each chart) and for DWWT for 1 kg of recovered P (all other lines). For the dairy LCAs, the different markers for each study and product represent different P recovery rates (one marker represents several P recovery technologies if the recovery rates are the same). Note the logarithmic scale.

have a lower impact because the incineration process was not included (T13–19 and T22). Indeed, among the technologies in the Amann et al. (2018) study, which does not include impacts from the incineration process in the LCA, all the technologies which recover P from sludge have a higher impact than those that start with ash. Linderholm et al. (2012) and Svanström et al. (2017), on the other hand, found that technologies recovering P from ash (T20–21) have the highest impacts when incineration is included. The technology that includes AD and therefore represents a larger system is not surprisingly among the highest (T7), but it has to be remembered that system expansions have

been removed from these results so that any potential gains from gas or energy products from anaerobic digestion or incineration are not considered. It should also be mentioned that the system boundary for product use is not completely consistent. Some of the products need more processing before they can be used as fertilisers, and some are more or less ready for use. In particular, the RecoPhos® technology (T14) adds phosphoric acid to increase the P concentration, while the AshDec® technology (T18–21) generates a depolluted ash that will be sent for fertiliser production. These differences in system boundaries considered, a comparison between the extracted results for different P recovery technologies generally shows that lower impacts are demonstrated by technologies that recover P from the liquid effluent or start with an ash if the incineration is not included in the assessment. Those that start from ash and where incineration was included are instead grouped with technologies that recover P from sludge at the higher end.

Going into more detail on hot spots and influencing factors, most of the methods that recover P from the liquid phase (T1–8) have a low contribution to CED owing to a low demand of energy and input chemicals. The effect of the recovery of P from the liquid is the reduced demand for flocculating agents otherwise needed for sufficient P removal during wastewater treatment (Amann et al., 2018); which needs to be considered if this type of P recovery is considered for an existing site. In the case of P recovery from sludge solids (T9–12), the CED is primarily due to energy and chemical demands. For example, the wet chemical extraction reported by Amann et al. (2018) requires citric acid, sodium hydroxide, and sulfuric acid, which are energy-intensive in their production. In the case of the acid wet chemical and wet oxidation processes of T11 (PHOXNAN technology), a higher CED is related to its demand for oxygen and electricity, and to the disposal and treatment of the remaining solids and heavy metal slag. For T7, the P recovery technology assessed by Zhang et al. (2020), its CED is particularly high because it includes the AD which we consider is a potential overlap with a wastewater treatment process. In the case of T14, phosphoric acid was added to ash with a P content of 8.5% (Egle et al., 2015) to make a commercial product. This influences the CED and puts RecoPhos® technology among those with a higher impact than those that did not include incineration.

With regard to climate impact, this impact often correlates with CED. A few additional points raised by the reviewed studies are provided here. For nutrient recovery from the liquid phase by struvite precipitation and ammonia stripping (T6), the climate impact was largely due to emissions related to the heat demanded by the ammonium stripper (Kjerstadius et al., 2017). For wet chemical leaching from sludge (T9 and T11), the greenhouse gas emissions are primarily related to the production of the chemicals used (citric acid, sodium hydroxide, and sulfuric acid) and the high demand for coke and natural gas used during sludge mineralisation (Amann et al., 2018). Technologies which recover P from ash require higher temperatures; therefore, more energy is required for these processes, which influences the climate impact (Linderholm et al., 2012). This last point is seen only for T20–21 in Fig. 4, as all other ash-related technologies shown exclude incineration.

Also, for the acidification, similar patterns are seen as for CED and climate impact. However, no technologies involving incineration have reported the impact of acidification. As will be further discussed later, this creates a potentially important knowledge gap, as the acidification impact is high in relation to that of DWWT and would likely be even higher if incineration is included. More studies should be conducted, and methods to reduce this impact related to P recovery should be explored. Technologies that recover P from the liquid phase are generally those with a lower acidification impact. Factors that have been reported to influence acidification impacts are electricity use and NH_4 emissions to air during stripping and struvite or calcium phosphate formation, which therefore require careful pH adjustment (Rodriguez-Garcia et al., 2014).

The results shown in Fig. 4 for the treatment of DWW were calculated for an unmodified DWWT and with the P recovery rates provided by Egle et al. (2015). It is not likely that the resulting impact when P recovery is installed at an existing site would be exactly the sum of the impact of the P recovery and the impact of the DWWT, as some alterations would likely be made if P recovery was introduced in a dairy context or if P recovery technologies were adapted to fit the new source flow; however, this comparison reveals orders of magnitude and things to pay attention to. Comparing the impacts from DWWT to those for P recovery (by matching the same marker in the uppermost line to one in any other line in Fig. 4), it is clear that P recovery technologies generally have a lower CED, and climate impact and a higher acidification impact compared to DWWT. However, there are some exceptions, in particular, when the CED and climate impacts of DWWT were already low in relation to Table 1, which was discussed earlier, and when recovery technologies received a high impact from the use of chemicals, such as precipitants, and included incineration.

It should be noted that any benefits related to the ultimate use of recovered P products were removed in our study to allow for consistent system boundaries, and potential differences between products, for example, plant availability and method for application, are therefore not captured. It is recommended that a full life cycle study be made of a system that contains both relevant parts of the dairy, on- or off-site P recovery, and transport, spreading, and use of recovered P products, once data of sufficient quality are available. It should also be mentioned that the current study only considers operation of the plants. Impacts related to construction could be added in future studies, especially when an existing plant is compared to a new one that is to be built. However, in any process with a large throughput of energy or materials and a long service life, such impacts are usually small compared to the operation (Svanström et al., 2017).

According to the results of this study, it seems clear that installing P recovery as part of or after DWWT will normally not incur large additional environmental costs compared to the current DWWT with regard to climate impact or energy use.

Recent LCA data on mineral fertiliser production are scarce. The reported climate impact of diammonium phosphate (DAP) (Zhang et al., 2017), which is the most widely used P-containing fertiliser, is 17 kg CO_2 eq/kg P. The P in this product was obtained from phosphate rock, and the product also contains some nitrogen. The authors state that the phosphoric acid entering the fertiliser production is responsible for almost half of the total impact; the low efficiency of use of phosphate rock and the heavy burden of pollutants emitted from phosphate mining are the main contributors (Zhang et al., 2017). The reported impact was in the same range as many of the results extracted in the present study (see the vertical line inserted in Fig. 4a). We can therefore assume that P recovered from DWW can likely replace mineral fertilisers without a considerable increase in environmental impacts, with the exception of some technologies that might need to be optimised or avoided.

The reader should be aware of some differences in the impact categories in this work. For example, the IPCC's recommended global warming potential values changed from the fourth to the fifth assessment report, increasing the characterisation factor for methane by 12% and decreasing it for nitrous oxide by 12%. The reports reviewed here include results from before and after this change and the consequential changes to LCIA methods like ReCiPe (see SM, section 7). It is infeasible to compensate for these changes given the absence of emission data by substance for all studies, however given that the results in Fig. 4 span orders of magnitude, we believe this change would not alter our qualitative conclusions.

It is also important to mention that potentially important environmental impact categories in this context were not fully captured in the comparison, for example eutrophication and resource use and depletion. Eutrophication is typically considered in LCA studies on dairy plants and is relevant for the assessment of any WWT, as this is an impact that the WWT itself aims to mitigate. Interestingly eutrophication was not always assessed in the literature on P recovery technologies (and never in a way that allowed cross-comparisons between the two groups of studies). In fact, in some of the reviewed LCA studies on P recovery

technologies, the eutrophication indicator was questioned because of its claimed inability to describe specific local conditions (Amann et al., 2018). Bradford-Hartke et al. (2015), Rodriguez-Garcia et al. (2014), and Zhang et al. (2020) found a significant eutrophication impact owing to the P recovery process. For AshDec® technology, the freshwater eutrophication potential (FEP) was found to be insignificant compared to other environmental impact categories (Bäfver et al., 2013; Heimersson et al., 2016; Svanström et al., 2017). As problems related to eutrophication and P resource depletion are likely the main reasons for P recovery in dairy products, further studies are needed to shed light on these potential issues. Regarding resource depletion, we believe that studies aiming to show the benefits of mineral recycling processes might reasonably be expected to include this indicator. It is to be hoped that detailed future LCA work will include detailed and disaggregated data on this indicator. From the point of view of P supply from dairy systems to other users, the presence of extensive agriculture in the upstream supply chain might also warrant the inclusion of land use and land use change as an indicator of resource use, in cases where allocation procedures are not considered to cut off wastewater from the upstream system.

4. Concluding remarks

It is challenging to find information on the life-cycle environmental performance of a combination of processes that does not yet exist. A meta-analysis of LCAs in literature was performed to provide information on a conceptual system involving P recovery in the context of DWWT. It was challenging to extract and compare results from different studies with different scopes and scales, but this article provides an example of how the lack of specific information at the early stages of process design can be overcome by collecting and refining data from earlier LCA studies. The study initially revealed that LCA studies on the dairy industry do not always include the DWWT process within their system boundaries. Eventually, nine relevant papers were found that assessed DWWT and six that assessed P recovery technologies. Differences in FUs, environmental impact categories, system boundaries, and type of inventory data used were considered in the meta-analysis and when needed, recalculations and rescaling was made.

Despite the treatment, in many cases, DWW still causes a significant part of the total eutrophication impact, primarily because of the remaining nutrients in the effluent. In general, the environmental impacts related to DWWT are strongly influenced by the scale of the dairy processing facility, as scale affects the possibilities of investing in technologies beyond the main production line.

The P recovery technologies examined here generally have a lower impact compared to DWWT with regard to climate impact and energy use, while the opposite is true for acidification. In general, the processes that recover from a liquid flow have a lower impact than when sludge is a P source. When sludge is incinerated and is recovered from an ash, the impact is typically even higher, but few of the considered technologies include incineration within the system boundary.

As pointed out and discussed in this paper, although the meta-analysis attempted to extract comparable information regarding two gate-to-gate systems, some gaps and overlaps remained and influenced the comparison. The boundary towards the further production of fertilisers was likely not consistent and any impacts or benefits related to the use of P products in agricultural activities were not included; therefore, further studies are needed.

Given the scope of the present study and the limited amount of data available in literature that fulfilled the requirements, we still deem this method of performing a meta-analysis of earlier LCAs as a useful alternative in the early stages of technology development, and also for this case. The analysis undertaken here extended our knowledge of the life cycle environmental impacts that can be expected of P recovery in a dairy context and provided useful guidance to the further technology development and environmental assessment within the REFLOW ETN project. The generation of additional empirical information on P recovery technologies for DWW will help improve the accuracy and relevance of future studies. In designing P recovery for dairy contexts, particular attention should be paid to the impact of acidification, and LCA studies should also consider eutrophication and resource depletion.

CRediT authorship contribution statement

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

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

Data will be made available on request.

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Appendix A. Supplementary data

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References

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resour. Conserv. Recycl. 130, 127–139.

Ashekuzzaman, S.M., Forrestal, P., Richards, K., Fenton, O., 2019. Dairy industry derived wastewater treatment sludge: generation, type and characterization of nutrients and metals for agricultural reuse. J. Clean. Prod. 230, 1266–1275.

Bradford-Hartke, Z., Lane, J., Lant, P., Leslie, G., 2015. Environmental benefits and burdens of phosphorus recovery from municipal wastewater. Environ. Sci. Technol. 49 (14), 8611–8622.

Brazzale, P., Bourbon, B., Barrucand, P., Fenelon, M., Guercini, S., Tiarca, R., Mainar, M. S., 2019. Bulletin of the International Dairy Federation 500: Wastewater Treatment in Dairy Processing Innovative Solutions for Sustainable Wastewater Management. IDF, Brussels.

Bäfver, L., Renström, C., Fahlström, J., Enfält, P., Skoglund, N., Holmén, E., 2013. Sam bränsleblandningar – Förbränning och fosforutvinning. In: Swedish, Co-combustion Fuel Mixes – Combustion and Phosphorus Recovery. S P Sveriges Tekniska Forskningsinstitut, Borås, Sweden.

Costea, D., Ghinea, C., 2021. Life cycle assessment of wastewater from dairy industry. Food and Environment Safety Journal 20.

Dalla-Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., De-Marchi, M., 2017. Environmental life cycle assessment of Italian mozzarella cheese: hotspots and improvement opportunities. J. Dairy Sci. 100 (10), 7933–7952.

Demirel, B., Yenigun, O., Onay, T.T., et al., 2005. Anaerobic treatment of dairy wastewaters: a review. Process Biochem. 40 (8), 2583–2595. In: https://doi.org/10.1016/j.procbio.2004.12.015.

Djekic, I., Miocinovic, J., Tomasevic, I., Smigic, N., Tomic, N., 2014. Environmental life-cycle assessment of various dairy products. J. Clean. Prod. 68, 64–72.

EDA, 2018. Economic Report 2017/18. EDA (European Dairy Association).

Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. Resour. Conserv. Recycl. 105, 325–346.

Eide, M.H., 2002. Life Cycle Assessment (LCA) of industrial milk production. Int. J. Life Cycle Assess. 7 (2), 115–126.

European Commission, 2006. Draft Reference Document on Best Available Techniques in the Food, Drink and Milk Industries. JRC, Seville.
European Commission, 2009. Economic Impact of the Abolition of the Milk Quota Regime. JRC, Seville. https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/key_policies/documents/ext-study-milk-quota-full-report_2009_en.pdf.
European Commission, 2016. Circular economy: new Regulation to boost the use of organic and waste-based fertilisers (MEMO/16/826). Brussels. https://ec.europa.eu/commission/presscorner/detail/en/IP_16_827.
European Commission, 2017. Communication on the 2017 list of critical raw materials for the EU. https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF.
European Commission, 2019. Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) - JRC118627. Publications Office of the European Union, Luxembourg.
FIL-IDF, 2015. A Common Carbon Footprint Approach for Dairy Sector. The IDF Guide to Standardlife Cycle Assessment Methodology. International Dairy Federation, Brussels.
Finnegan, W., Goggins, J., Clifford, E., Zhan, X., 2017. Environmental impacts of milk powder and butter manufactured in the Republic of Ireland. Sci. Total Environ. 579, 159–168.
Gabrić, D., Galić, K., Timmerman, H., 2016. Chapter 31 - Cleaning of Surfaces. Handbook of Hygiene Control in the Food Industry. Woodhead Publishing, San Diego, pp. 447–463.
González-García, S., Hospido, A., Moreira, M.T., Feijoo, G., Arroja, L., 2013. Environmental life cycle assessment of a Galician cheese: san Simon da Costa. J. Clean. Prod. 52, 253–262.
Harder, R., Wielemaker, R., Larsen, T.A., Zeeman, G., Öberg, G., 2019. Recycling nutrients contained in human excreta to agriculture: pathways, processes, and products. Crit. Rev. Environ. Sci. Technol. 49 (8), 695–743.
Heimersson, S., Svanström, M., Laera, G., Peters, G., 2016. Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems. Int. J. Life Cycle Assess. 21 (8), 1197–1212.
Hermansson, F., Janssen, M., Svanström, M., 2019. Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. J. Clean. Prod. 223, 946–956.
Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., Norris, G., 2013. Life cycle assessment of cheese and whey production in the USA. Int. J. Life Cycle Assess. 18 (5), 1019–1035.
Kjerstadius, H., Saraiva, A.B., Spangberg, J., Davidsson, A., 2017. Carbon footprint of urban source separation for nutrient recovery. J. Environ. Manag. 197, 250–257.
Linderholm, K., Tillman, A.M., Mattsson, J.E., 2012. Life cycle assessment of phosphorus alternatives for Swedish agriculture. Resour. Conserv. Recycl. 66, 27–39.
Numviyimana, C., Warchoł, J., Khalaf, N., Leahy, J.J., Chojnacka, K., 2022. Phosphorus recovery as struvite from hydrothermal carbonization liquor of chemically produced dairy sludge by extraction and precipitation. J. Environ. Chem. Eng. 10 (1), 106947.
Rodriguez-Garcia, G., Frison, N., Vázquez-Padín, J.R., Hospido, A., Garrido, J.M., Fatone, F., Bolzonella, D., Moreira, M.T., Feijoo, G., 2014. Life cycle assessment of nutrient removal technologies for the treatment of anaerobic digestion supernatant and its integration in a wastewater treatment plant. Sci. Total Environ. 490, 871–879.
Schröder, J.J., Cordell, D., Smit, A., Rosemarin, A., 2010. Sustainable Use of Phosphorus. Wageningen UR.
Shilpi, S., Seshadri, B., Sarkar, B., Bolan, N., Lamb, D., Naidu, R., 2018. Comparative values of various wastewater streams as a soil nutrient source. Chemosphere 192, 272–281.
Skrydstrup, J., Larsen, S.L., Rygaard, M., 2020. Eco-efficiency of water and wastewater management in food production: a case study from a large dairy in Denmark. J. Ind. Ecol. 24 (5), 1101–1112.
Slavov, A.K., 2017. General characteristics and treatment possibilities of dairy wastewater - a review. Food Technol. Biotechnol. 55 (1), 14–28.
Stanchev, P., Vasilaki, V., Egas, D., Colon, J., Ponsá, S., Katsou, E., 2020. Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy. J. Clean. Prod. 261.
Svanström, M., Heimersson, S., Peters, G., Harder, R., I'Ons, D., Finnson, A., Olsson, J., 2017. Life cycle assessment of sludge management with phosphorus utilisation and improved hygienisation in Sweden. Water Sci. Technol. 75 (9–10), 2013–2024.
Vagnoni, E., Franca, A., Porqueddu, C., Duce, P., 2017. Environmental profile of Sardinian sheep milk cheese supply chain: a comparison between two contrasting dairy systems. J. Clean. Prod. 165, 1078–1089.
Vergé, X., Maxime, D., Dyer, J.A., Desjardins, R.L., Arcand, Y., Vanderzaag, A., 2013. Carbon footprint of Canadian dairy products: calculations and issues. J. Dairy Sci. 96, 6091–6104.
Yan, M.J., Holden, N.M., 2019. Water use efficiency of Irish dairy processing. J. Dairy Sci. 102 (10), 9525–9535.
Yapıcıoğlu, P., Yeşilnacar, M.I., 2020. Energy cost assessment of a dairy industry wastewater treatment plant. Environ. Monit. Assess. 192 (8), 536.
Zhang, F., Wang, Q., Hong, J., Chen, W., Qi, C., Ye, L., 2017. Life cycle assessment of diammonium- and monoammonium-phosphate fertilizer production in China. J. Clean. Prod. 141, 1087–1094.
Zhang, Y., Zhang, C., Qiu, Y., Li, B., Pang, H., Xue, Y., Liu, Y., Yuan, Z., Huang, X., 2020. Wastewater treatment technology selection under various influent conditions and effluent standards based on life cycle assessment. Resour. Conserv. Recycl. 154.