REFLOW

"Phosphorus REcovery for FertiLisers frOm dairy processing Waste"

Grant Agreement: 814258

Deliverable 3.6

Report on first stage environmental assessment for project guidance

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814258. The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union"

DOCUMENT SUMMARY

Deliverable Title	Report on first stage Environmental Assessment for project guidance		
Due Date	Month 24 (31/12/2020)		
Version	Final v1.0		
Deliverable Type	Report		
Deliverable Lead	STRANE		
Related Work package	WP 3		
Author(s)	Marta Behjat (Chalmers)		
Reviewer(s)	Magdalena Svanström (Chalmers)		
Contributor(s)			
Communication level	PU	Public	☒
	PP	Restricted to other programme participants (including the Commission Services)	☐
	RE	Restricted to a group specified by the consortium (including the Commission Services)	☐
	CO	Confidential, only for members of the consortium (including the Commission Services)	☐
Grant Agreement Number	814258		
Programme	H2020-MSCA-ITN-2018		
Start date of Project	01/01/2019		
Duration	48 months		
Network coordinator	UNIVERSITY OF LIMERICK		

DOCUMENT HISTORY

Issue Date	Version	Changes Made / Reason for this Issue
29/01/2021	V0.1	Initial Version
17/02/2021	V0.2	Format updates – final review
18/02/2021	V1.0	Submission

TABLE OF CONTENTS

LIST OF ABBREVIATION

AC	Activated Sludge
AP	Acidification Potential
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CED	Cumulative Energy Demand
D	Deliverable
DAF	Dissolved Air Flotation
DCP	Dicalcium Diphosphate
DPWW	Dairy Processing Wastewater
DM	Dry Matter
EDA	European Dairy Association
EU	European Union
EP	Eutrophication Potential
FEP	Fresh Water Eutrophication Potential
FU	Functional Unit
GHG	Green House Gases
GWP	Global Warming Potential
IDF	Industrial Dairy Federation
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MAP	Magnesium Ammonia Phosphate
MEP	Marine Eutrophication Potential
P	Phosphorus
SSA	Sewage Sludge Ash
WP	Work Package
WWTP	Wastewater Treatment

1 Introduction

According to the European Dairy Association (EDA), the dairy industry is a very important part of the European agri-food sector, the biggest milk producer in the world, accounting for approximately 160 million tonnes of milk (22% of the world´s total milk production) (EDA, 2018). After the abolition of European milk quota in 2015, the dairy sector increased, around 2.8% annual growth (A. K. Slavov, 2017), and it also means that more wastewaters need to be treated (S. M. Ashekuzzaman et al., 2019). This strong sector and its large amount of wastewater produced, contribute to addressing the growing demand for food, but it could also lead to an increase in environmental impacts. A potential solution to reduce the environmental impacts could be to treat the dairy processing wastewater (DPWW) in a sustainable manner.

The dairy industry plays an important role in the wastewater treatment sector (S. M. Ashekuzzaman et al., 2019). These dairy processing wastewaters consist of milk residues, acid or alkaline compounds, detergents and sanitizing agents and are characterized by high concentration of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), nutrients and suspended solids.

In recent years, the interest has increased in technological development for nutrient recovery from organic waste streams. An important nutrient considered is phosphorus (P).

Phosphorus is a chemical element that does not occur in nature other than in the form of phosphate, a chemical derivate of phosphoric acid. There are several forms of phosphate in nature, but the most commonly used for human activities is derived from rock-phosphate. In this rock, phosphorus is present at an appreciable concentration in only a few minerals, primarily fluorapatite (G. M. Filippelli, 2008)

The phosphorus is important for economic growth in several industrial sectors. The fertilizers and food industries are the dominating user sectors of phosphate rock, and agricultural sectors are the main end users of phosphorus, but Europe does not have significant phosphate mines and the concentration of rock phosphate is located in geopolitically sensitive regions which might pose a threat to the European food security (J.J. Schröder et al., 2010).

Phosphorus is a finite resource, a non-renewable element that, because of economic growth, will be a limited resource in the future. From 1983 to 2013, the phosphate rock price increased and its global consumption increased by 25% (Z. Bradford-Hartke et al., 2015). The awareness of this increasing demand brought the European Commission to declare phosphate as a critical raw material in 2014 (European Commission, 2017). So, an alternative source to rock phosphate is needed.

In order to simultaneously find a solution to the large volume of DPWW and to respond to the rock phosphate crisis, the EU, through its Circular Economy Package, has prioritized the recovery and safe reuse of plant bioavailable P from food and municipal waste streams, including DPWW (European Commission, 2016).

REFLOW, an interdisciplinary European Training Network involved in research focusing on dairy processing, fertilizer production and phosphorus recycling, is analysing the important technical, socio-economic and environmental challenges associated with the recovery of phosphorus from DPWW and its recycling into fertilizer products.

The work described in this report is part of the Work Package 3 in the REFLOW project (EC Grant No. 814258), which intends to determine to which extent different methodologies for P-recovery from wastewater are environmentally appropriate to be applied in combination with existing DPWW treatment. A commonly used tool for estimation of the environmental impacts associated with the dairy process, wastewater treatment and P-recovery technology, is Life Cycle Assessment (LCA). This report describes the LCA methodology that will be applied to study the environmental impacts of the REFLOW scenario and it presents and elaborates on some findings from a literature review of earlier LCA studies on dairies and on P recovery technologies.

2 Materials and methods

2.1 Investigated Scenario

The aim of the REFLOW project is to recover the phosphorus from the DPWW and then to use it in the agricultural sector. The REFLOW project is mainly focused on the recovery and use of specific P-products, such as dicalcium phosphate (DCP) and struvite (magnesium ammonium phosphate – MAP), or by-products rich in phosphorus, obtained from the wastewater treatment, such as biofertilizer, ash and hydrochar. These products will be recovered through the application of further technologies in the DPWW treatments. The DPWW is the result of a series of processes in the dairy industry, where the amount and characteristics of the wastewater depend primarily on the final dairy product obtained at the end of the dairy chain. For this kind of study, two industrial situations will be considered for their potential effects on the environment: dairy industry, in particular its wastewater treatment, and P-recovery technologies. The combined knowledge about these will generate an understanding for the challenges and opportunities for P-recovery in a dairy context. An overview of the phosphorus flows in the considered systems is shown in figure 1.

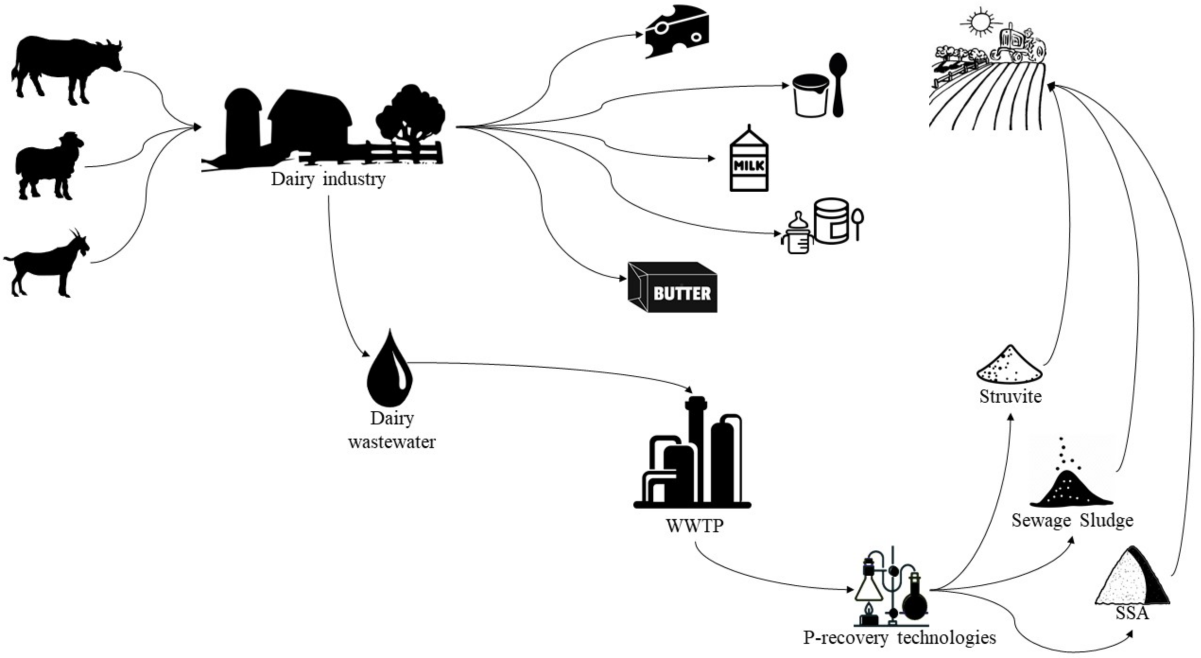

Figure 1. Representation of the phosphorus flows from the raw milk to the P-products recovered and used in agricultural activities. Other to the raw milk and dairy products, DPWW are rich in P and used to recover the P-products (Struvite, sewage sludge and sewage sludge ash (SSA)).

2.1.1 Dairy industry

The dairy industry is one of the most important food sectors in the world, but because its size and types of manufactured products vary largely, it is not easy to give a general characteristic. The dairy plant can be divided into different production sections and the generation of DPWW, in terms of volumes and composition, is related to the type of production, processes and practices used in the dairy processing industry (P. Brazzale et al., 2019). Figure 2 shows a flow sheet of a typical dairy process. Irrespective of the dairy product or the origin of milk, from cow, goat or sheep, each dairy plant has a section where milk is delivered and stored. After these steps, the destiny of the milk changes based on the different products that are made: liquid milk, powder milk, cheese, butter or yogurt (see figure 2). The milk powder is the result of a dewatering and drying process of pasteurized milk. Butter is made from the cream obtained from the skimming process. Regarding the cheese, there are several varieties of cheese and they are the result of different types of production process, but generally the type of cheese is the results of the curd treated in a certain way. Yoghurt, on the other hand, is obtained after the homogenization of pasteurized milk and mixing with bacteria cultures and the subsequent fermentation. The volume of incoming water and the amount and composition of the wastewater of each specific dairy production process varies.

2.1.2 DPWW treatment

The management of DPWW normally consists of three steps involving different treatments: the first treatment removes fats, oils, and greases through a dissolved air flotation (DAF); the secondary treatment is an anaerobic and/or aerobic treatment performed by technologies based on biological processes; and the tertiary treatment is focused on the removal of nutrients through chemical or biological removal (P. Brazzale et al., 2019; S. M. Ashekuzzaman et al., 2019) (Figure 3). With these three steps, three different sludges are generated: primary or DAF sludge, secondary or bio-chemical treated activated sludge (AC), and tertiary sludge.

2.1.3 P-recovery technology

In recent years, the interest for a sustainable approach has increased in technological development for P-recovery from wastewater. Indeed, a sustainable method consists on the recovery of P-products, from the sludge, ash, and the liquid phase generated during the DPWW treatment. In order to that, the sludge and the soil, other to be spread in farmlands, with the liquid phases, are considered the main income sources for the P-recovery technologies(see figure 4).

The main product recovered from the liquid phase is struvite, that can precipitate from all kinds of wastewaters. The struvite production system includes sludge thickening and dewatering, to get a liquid phase, which is then subjected to a crystallization or precipitation process, with the addition of magnesium chloride and sodium hydroxide (K. Linderholm, 2012). The precipitation process is controlled by a combination of magnesium addition and pH control. This process is applied to treat the liquids produced after first or second treatment of the DPWW treatment, but also to the tertiary sludge, after it has been further dewatered. The tertiary sludge is rich in phosphorus. Regarding the digested sludge produced after the DPWW treatment, rich in nutrients, it can be incinerated to generate ash that can be used to recover further P-products. The ash from mono-incineration of sludge can be mixed with chlorine donors and compacted in pellets that are exposed to high temperature (1000°C) to let metals evaporate (K. Linderholm, 2012). In some cases the ash can also be used directly on the field, but the bioavailability of P in the ash is low (H. Herzel et al., 2016). The common treatment for municipal wastewater that is applied to produce a sludge suitable to be spread, consists in biological treatment followed by a chemical precipitation with aluminium and iron, to produce a sludge rich in P (2.8% of DM) (K. Linderholm, 2012).

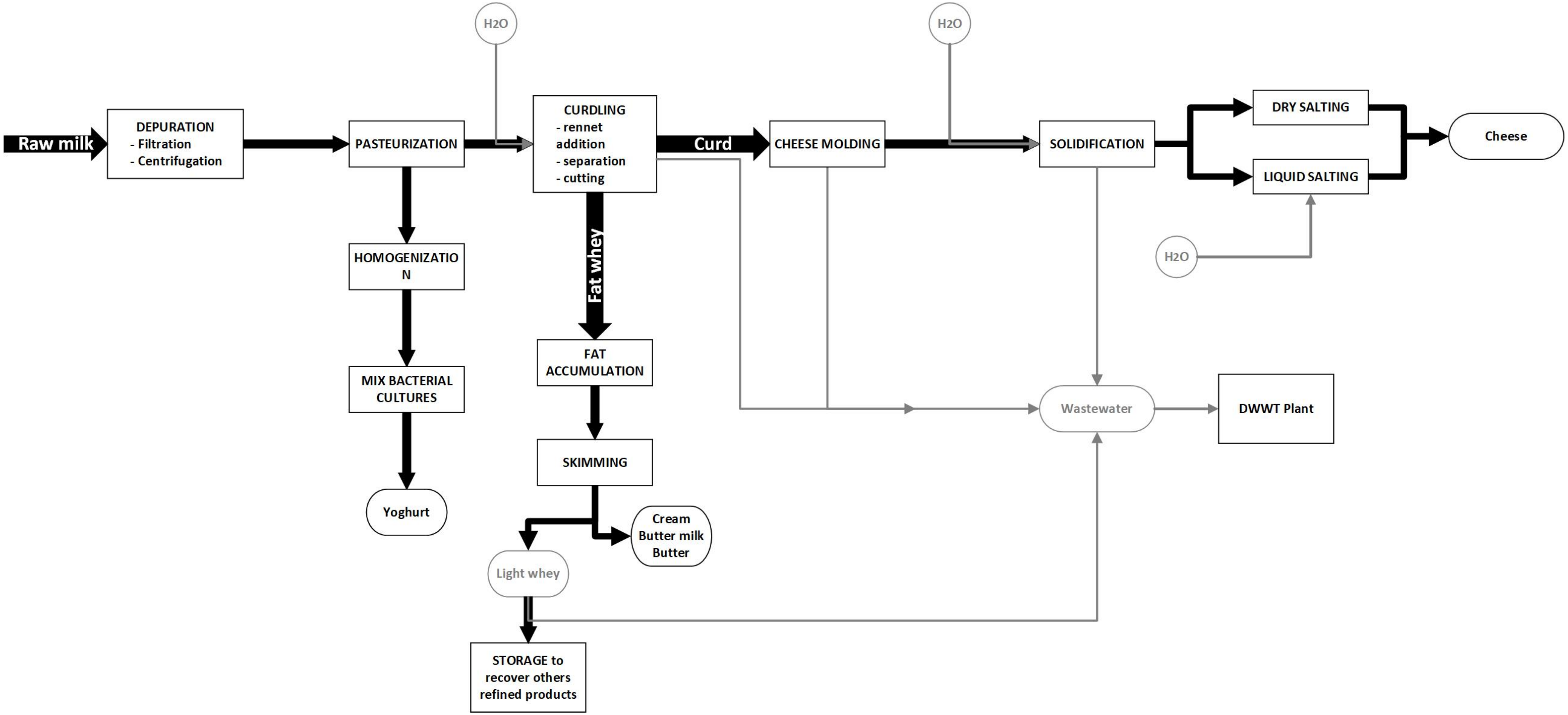

Figure 2. General description of the production processes of dairy products, indicating also the use of water and the wastewater production.

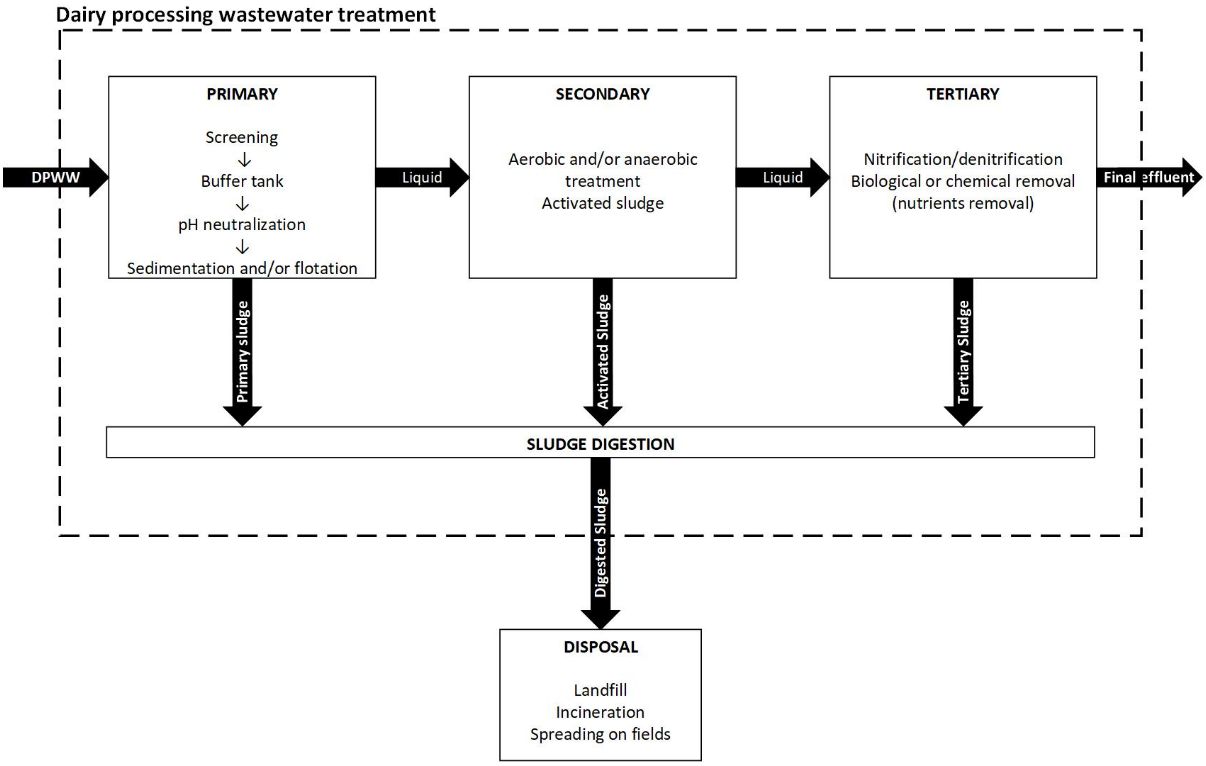

Figure 3. Flowchart of a typical DPWW treatment process. Three different sludges are generated, mixed and treated based on the need final disposal (landfill, incineration, or spreading on the fields).

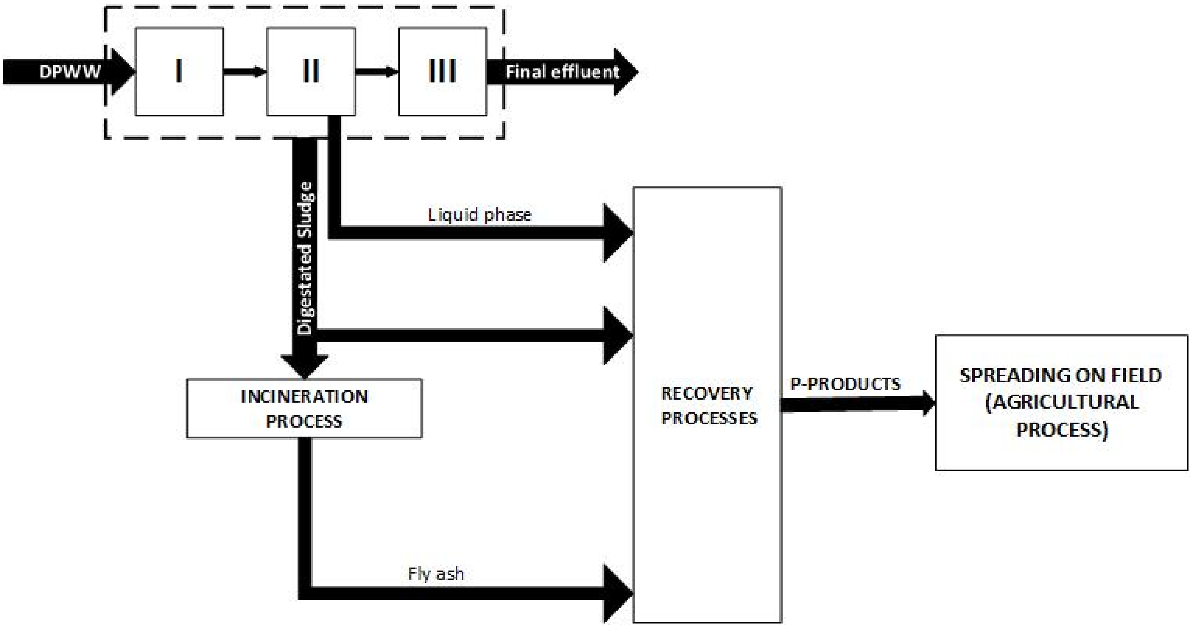

Figure 4. Scenario of the of the methodology applied in REFLOW to recover P-products from the DPWW treatment to replace fertilizer in agriculture

2.2 Environmental assessment

The environmental assessment will be performed through 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, as described in the international standard, ISO14044, consists of four phases: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of the results. The assessment of the REFLOW system will eventually include the dairy industry as well as the P-products recovery and use (see figure 5). Important methodological choices in each of the four phases of LCA are further discussed below.

Early on, a deliverable (D 3.1), a literature review on the LCA methodologies adopted in these scenarios, was undertaken. The current study is built further on the collected knowledge discussed within D 3.1.

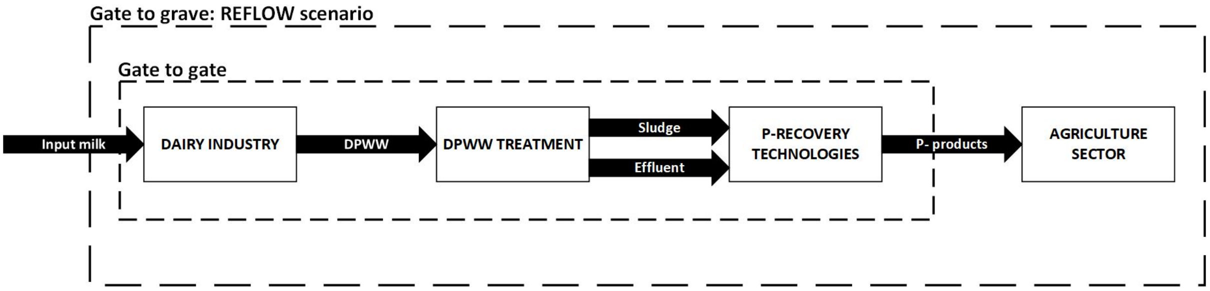

Figure 5. Representation of the system boundary of the LCA study. The REFLOW project intends to assess a gate-to-grave system, from the dairy industry to the replacement of the fertilizers with the REFLOW products (P-products recovered). In the present report, the agricultural sector will not yet be considered.

2.2.1 Goal and Scope

The LCA starts with the statement of the goal and scope of the study, which gives information about the purpose of the LCA study and the intended use of its results. The goal and scope definition consists in the description of the system boundaries, the function of the system, the functional unit (FU), the allocation methods, and the selection of environmental impact indicators. Assumptions and limitations are also taken in consideration during the goal and scope definition.

The main aim of the LCA in the REFLOW project is to make an environmental assessment of the REFLOW technologies as parts of a larger system, from the production of the dairy wastewater to the recovery and use of P-products. The goal of this study is to (1) analyse and compare the P-recovery technologies, applied in DPWW treatment, and (2) assess how much bigger the impacts of recycling processes are compared to the current wastewater management processes. An important aspect in this first evaluation is the identification of hotspots in terms of environmental impacts, in the REFLOW chain, to direct further process development efforts.

The system boundary

The system boundary of this study will cover a gate-to-gate system (see figure 5), from the input of raw milk at the dairy industry to the recovery of the final P-product. The P-recovered fertilizer use was not included in this first stage assessment.

Function and functional unit (FU)

The FU choice is a debatable step for the LCA in this study. According to literature (see D 3.1) two different functional units are typically considered for dairy industry activities and for P-recovery technology processes. For dairy industry, one kilogram of the final dairy product, packaged and ready to be distributed is the functional unit advised by the international dairy Federation (IDF) (FIL-IDF, 2010), while regarding P-recovery technologies, the mass of P-recovered is typically recommended as a FU (C. Remy & F. Kraus, 2019), but other functional units are possible and have been applied in different contexts. Ultimately, this has to depend on the goal of the study. Since the function of the system in this study is to produce P-products, through the use of technologies which recover phosphorus from DPWW, ultimately, the mass of P recovered could be a relevant FU.

However, this first LCA could not rely on primary data input from the project and the evaluation therefore relies primarily on LCA data and results that could be extracted DPWW treatment system that included P recovery. Therefore, the assessment was done in two steps. The first involved looking into the impact related to dairies and in particular the wastewater treatment (WWT) but recalculating data in literature to correspond to 1 liter of milk input. In the second step, relevant P recovery technologies were explored using a FU of 1 kg of P product. Finally, by estimating a P content in the DPWW from the dairy for a certain milk input, these two parts could be combined, or rather, compared. At this early stage in technical development, it was not possible to model a dairy that included P recovery in its WWT.

Allocation

The considered system, which includes the dairy industry, WWT process, and the P-recovery technologies, produces more than one product. This system is therefore a multioutput system and an allocation approach is needed since not all products will be included in the FU. Through the allocation approach the environmental load of the system is divided between or allocated in other ways to the different dairy products, to any products that are generated in the wastewater and sludge management including the final phosphorus recovered.

With the FUs and system boundaries employed in this study, this means that we are eventually interested in what impact from the dairy and from the different other parts of the system that should be allocated to the phosphorus generated in the phosphorus recovery and any by-products could be considered either (1) through a subdivision that allows for selecting which processes and parts of the system should be considered for the phosphorus product, (2) a system expansion that would credit other outputs for what they can replace or (3) a method that allows for dividing impacts between outputs based on some common trait like mass, energy content, economic value, or similar.

Since the present study included extracting data and impacts from earlier literature, allocations that had been employed in earlier studies had to be identified and sometimes considered. In particular, the allocation approach for dairies, which are multioutput systems and that employ an output-based FU involved allocations that has to be considered.

A relevant allocation method that should be considered for this assessment is the Physic-chemical matrix allocation. This allocation is a method designed and strongly recommended by the IDF for dairy industry (A. J. Feitz et al., 2007) (FIL-IDF, 2010). “This allocation method is the product of an extensive process of subtraction/substitution to determine average resource use and wastewater emissions for individual dairy products” (A. J. Feitz et al., 2007).

This method consist on the production of a matrix of resource efficiency coefficients, estimated from initial literatures and companies, versus dairy products (A. J. Feitz et al., 2007). But despite this recommendation, physical or economic allocation are also heavily used in published studies.

Despite that, further studies are necessary to define the most suitable allocation to use for the REFLOW scenario. The choice of the allocation method depends on the system boundary. If the Physic-chemical matrix allocation is a good option for the LCA on the dairy process, it would not be the same for the P-recovery technology process.

Environmental impact indicator

For a satisfactory selection of environmental impact indicators in LCA, it is important to take in consideration two aspects. First, the environmental impact categories should be of relevance for the system under study. Second, the selection of indicators will rely on practicability and data availability (C. Remy & F. Kraus, 2019). Considering these two aspects, the environmental impact indicators that were considered for this study were global warming potential (GWP); cumulative energy demand (CED), acidification potential (AP); and eutrophication potential (EP) for freshwater, marine and terrestrial systems. The selected environmental indicators were calculated at midpoint level. Table 1, besides showing the considered indicators and the recommended indicator models (C. Remy & F. Kraus, 2019), describes how the environmental impact categories are affected by the process under study.

Table 1. Selected set of LCA indicators for the environmental assessment of the P-products recovery from the DPWW.

Indicators models	**Indicators**	**Contribution**
IPCC	GWP (kg $CO_{2\ eq.}$)	E.g. greenhouse gas emissions related to the production of the chemicals used in the system, the transportation of milk, sewage sludge, wastewater, whey, ingredients, or chemicals, the energy production, as well as generated from the biological material itself throughout the dairy process and wastewater and sludge management, including P recovery.
ReCiPe	EP (kg $PO_4^{3-}{}_{eq.}$)	E.g. emissions with N and P from the WWTP
VDI 4600	CED (MJ)	E.g. energy used in cleaning operations and waste disposal, transportation, chemical use and production as well as for sludge digestion and incineration.
ReCiPe	AP (kg $SO_{2\ eq.}$)	E.g. emissions of acidifying substances related to energy and transportation as well as N in the wastewater that turns into ammonia

As in the allocation method, also the environmental impact indicator choice is strongly influenced by the system boundary. Considering that the REFLOW project is not interested in the dairy production process itself, the indicators selected for this assessment (table 1), have been chosen considering only the DPWW treatment and the P-recovery processes and their contributions to the environmental impacts.

Uncertainty and Limitations

Applying the LCA methodology to this system, certain limitations arise at multiple levels of this study. These limitations are due to limited knowledge about the topic research, data availability, and the methodological choices.

From the review of these articles it is clear that there is a limited knowledge on the considered technologies and environmental impacts of relevant systems. A limited number of earlier studies were found. A limitation is due to the limited knowledge that exist about the LCA of

DPWW treatment. With regard to LCA studies of P-recovery technologies, these articles refer to the application of the recovery technologies to municipal WWT. There is no information on the P-recovery technology applied to DPWW treatment.

Apart from this limitation of insufficient knowledge about the considered technologies and the environmental impacts, specific limitations lie in that data collection and methodological choices were not the same in reviewed studies. Environmental indicators and system boundaries (geographical and time horizon) tend to be inconsistent, which makes any comparison or extraction of data challenging:

- **Data collection:** the LCA in REFLOW will at this stage require data for two different major system parts, the Dairy Processing data (including the WWT), and P-recovery technology data. For the first kind of data, no surveys have yet been done for the REFLOW project in dairies, so the data used for the analysis have been collected and calculated from the literature review. Regarding the data relative to the P-recovery technologies, it was optimistically expected that some of this could be delivered by Work Package 1 (WP1) in the REFLOW project, which develops, uses and analyses these technologies to produce the REFLOW products. But because of the covid-19 situation, which disturbs the experimental plan of WP1, unfortunately, enough useful data could not be generated. So, also these data have been collected from the literature review.
- **The choice of environmental impact indicators**: the delimited choice to only a few indicators (see table 1 above) makes the work load for data collection manageable and to facilitate interpretation of the results. Other indicators, such as toxicity, land system change and change in biosphere and biodiversity, despite their potential importance, have been not included. When fertilizer use in agriculture is included in later stages of the LCA work, the choice of environmental impact indicators will be revisited and, if needed, changed.
- **Geographical system boundary choice**: considering that the REFLOW project is a European Training Network and that Europe is the biggest milk producer in the world, the environmental assessment will be delimited to only the dairy industry located in the European countries.
- **Time horizon choice**: two different times have been considered: the present, looking at existing technologies (processing and WWT) in the dairy, and the future, focusing on the P-recovery technologies that will be adapted to the DWW treatment. The assessment presented in the current report will not consider the implications of considering different technical development and changes in background systems that might take place in the coming ten years, but in later work in this WP, this will be considered and likely, scenarios representing both the present and the future (10 years for now) could be considered.

2.2.2 Life Cycle inventory (LCI)

The LCI is the "*phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle*" (ISO 14044, 2006). The LCI includes the construction of a model represented by a flowchart, in line with specifications provided in the goal and scope for system boundaries, data collection and calculation of the environmental loads of the system in relation to the FU (H. Baumann & Tillman, 2015).

Once the P-recovery technologies have been chosen, data for the LCA analysis is expected to be communicated from the WP1 of the REFLOW project and converted in relation to our FU (1 liter of raw milk, alternatively, 1 kg of recovered P). The aim of the current deliverable is partly to describe the LCA methodology that will be adopted to assess how different approaches to P-recovery from DPWW could influence the environmental impact.

It is expected that the following six types of data will be central:

- amount of incoming water
- amount of wastewater produced and treated
- chemical characteristics of the wastewater
- energy used in the dairy, the WWT and in the P-recovery process
- detergents and ingredients used in the dairy and in the WWT, and additives in the P-recovery process
- amount of P-products recovered.

A lot of these data will be collected during the inventory phase from several different sources. For the aim of this assessment, the data relative to the dairy processes could be collected directly from the industries, including also the DPWW treatment process data, while data relative to the P-recovery technologies data could be provided from WP1. As written above however, an expected limitation in this analysis is data availability. In this first step, data was collected solely from the literature review.

Table 2 summarises data that were collected from the review of LCA studies on dairies. Only studies that covered and were specific with regard to the wastewater treatment were selected. Water and wastewater data were collected and, in many cases, recalculated in order to give an understanding for the amount of water used and amount of wastewater produced when processing one liter of raw milk in the dairy. Additives data provide knowledge about the quality and the chemical characteristics of the wastewater. Energy data were considered with regard to how much energy is consumed to process one liter of raw milk, and also to treat the related amount of wastewater.

The analyse undertaken to date has not focussed on the LCI of the P-recovery technologies, it was possible to collect only a modest level of data from the literature review. Table 3 shows an example of data that has been collected from literature review on LCA studies on P-recovery technologies, for technologies selected to represent the recovery of P from the liquid phase and from the sludge ash. This data has been collected from a study (K. Linderholm, 2012), and recalculated for 1 kg of P-product. The energy data (table 3) refers to the energy needed for both the P-recovery process and the additives production process. During the P-recovery processes, in the case of this study, there are no greenhouse gas (GHG) emissions, except for the additives production. During the incineration of the sewage sludge, which generates the P-containing ash, GHG emissions are associated with the energy produced to be sold (K. Linderholm, 2012). GHG emissions of the incineration process, have not been included in the inventory.

2.2.3 Life Cycle impact assessment (LCIA)

The LCIA aims to describe the environmental consequences of the environmental loads quantified in the inventory analysis(H. Baumann & Tillman, 2015). The impact assessment is the result of an environmental load “translation” from the inventory results into environmental impacts (H. Baumann & Tillman, 2015).

According to the ILCD Handbook (A.B. Heinrich, 2010), it is recommended to calculate the selected environmental impacts – GWP, EP, CED and AP – at midpoint level, and in order to assist this calculation, a LCA software package was used. Among all available LCA software, the OpenLCA will be considered for modelling the REFLOW system. This LCA is openly accessible and allows for a transparent assessment, so that the calculations and the quality of data can undergo third party review if that is deemed suitable. However, the first data treatment and preliminary calculations have been managed in Excel.

Due to lack of data at this stage, environmental impacts data, showed in the tables below (table 4 and table 5), are the result of a data collection and treatment process based on the literature review, and these data have thus not been calculated in an LCIA based on LCI in the project. These values have instead been generated through recalculation of impacts reported in literature to the FUs chosen in this study.

Table 4 shows the environmental impacts related to waste and wastewater treatment in the dairy industry, if 1 liter of milk is raw (FU). Only a few of these studies calculated the environmental impacts due to the DPWW treatment (light grey). The percentage values express how large the environmental impact potential due to the waste or wastewater management is in relation to the other activities involved in the dairy production.

In table 5, environmental impacts related to the second part of the REFLOW system included at this stage, the P-recovery technologies, are provided, but for studies selected from literature. These values were obtained for municipal wastewater and may therefore not be fully representative for the case where DPWW is used in the recovery process. These are the results for the comparing of environmental impacts of P-recovery in relation to the reference system (the municipal WWT). These data have been recalculated in relation to 1 kg of final P-product, to make a comparison identifying which of them contribute less to the environmental impacts, and in relation to 1 liter of raw milk for the comparison of P-recovery technologies in relation to the DPWW treatment.

Table 2. LCI for flows related to water and wastewater, gathered from LCAs on dairies in literature. Electricity input refers to the wastewater treatment. All data have been recalculated to correspond to the FU in this study: 1l of raw milk input to the dairy.

Articles	Product	Input water (l)	Wastewater (l)	Electricity input (kWh)		Thermal energy input (kWh)	Detergents-Cleaning Agents (g)	Ingredients (g)
				Dairy production	Wastewater			
W. Finnegan et al., 2017	Pwd milk	1.390	1.553	0.0545	0.0054	0.4619	2.575	
	Butter	0.826	1.289	0.0477	0.0058	0.0595	1.884	
I. Djekic et al., 2014	Pasteurized	2.509	2.509	0.0935		0.0170	5.339	
	UHT	2.111	2.111	0.0283		0.1303	6.537	
	Yoghurt	4.686	4.686	0.5793		0.2521	5.339	
	Cream	0.633	0.633	0.0253		0.0030	0.437	
	Butter	0.372	0.372	0.0121		0.0214	0.821	
	Cheese	3.873	3.873	0.0671		0.2589	10.436	
G. Mondello et al., 2018	Pecorino	9.261		0.2783		0.6796	0.723	
N. Palmieri et al., 2017	Mozzarella	2.230		0.0250		0.0039		
S. González-García, A. Hospido, et al., 2013	San Simon da Costa	0.610		0.0650		0.2859	1.166	2.115
S. González-García, E.G. Castanheira, et al., 2013	Mature cheese	2.969		0.1353		0.0005	17.250	
D. Kim et al., 2013	Cheddar	1.657	2.304	0.0737		0.1618	7.246	
	Mozzarella	3.103	2.583	0.1465		0.1482	11.972	
A. Dalla Riva et al., 2018	Asiago	5.443		0.1243		0.2204	3.765	5.576
H. C. M. Jr. Santos et al., 2017	Cheese	1.863	1.863	0.1072			1461.953	523.132
A. Flysjö et al., 2014	More products			0.2425				16.850
H.A. Aguirre-Villegas et al., 2012	Cheddar cheese			0.0468		0.4131	1.900	149.410
C.E. van Middelaar et al., 2011	Cheese						1.991	10.533
K. Nilsson et al., 2010	Butter DK	0.770		0.0574		0.2027		
	Butter DE	0.770		0.0574		0.2027		
	Butter FR	0.770		0.0574		0.2028		
C.S. Mahath et al., 2019	Milk	2.128	1.892	0.0124		0.0044	0.590	

	Ghee	0.709	0.631	0.0040		0.0009	0.164	
	Butter	0.840	0.747	0.0048		0.0036	0.894	
	Curd	3.485	3.100	0.0673		0.0138	4.658	
	Sambaran	3.840	3.416	0.0693		0.0142	0.533	
	Cream	0.553	0.492	0.0032		0.0011	0.154	
	Ice cream	5.505	4.896	0.0977		0.0004	3.504	
	Sip up	4.013	3.569	0.0712		0.0003	2.510	
	Ice cream candy	3.013	2.680	0.0535		0.0002	1.884	
F. Canellada et al., 2018	Cheese	7.735		0.3109			2.903	1.531
G. Doublet et al., 2013	Pasteurized milk	0.753	0.769	0.1230		0.4292		3.821
	Sour Cream	0.225	0.229	0.0367		0.1281		
	Yoghurt natural	0.322	0.367	0.0489		0.3874		
	Curd	1.239	1.346	0.6463		1.3782		
	Butter	1.239	1.346	0.6463		1.3782		
	Fresh cheese	1.239	1.346	0.6463		1.3782		
	Soft cheese	1.547	1.515	0.1077		0.3132		
	Semi soft cheese	1.239	1.346	0.6463		1.3782		
	Cream cheese	1.547	1.515	0.1077		0.3132		
X. Vergé et al., 2013	Cheese	2.136	2.421	0.0000		0.1246	2.648	
	Cottage	0.464	0.525	0.0000		0.0997	2.539	
	Creams	0.515	0.584	0.0000		0.0831	0.348	
	Sour Cream	0.618	0.700	0.0000		0.0997	0.450	
	Yogurt	1.545	1.751	0.0000		0.4984	0.523	
	Fluid milks	1.296	1.469	0.0000		0.2090	0.734	
	Buttermilk	0.773	0.876	0.0000		0.1246	0.543	
	Frozen dairy product	3.090	3.502	0.0000		0.0150	3.880	
	Powders	1.082	1.226	0.0000		0.8472	2.216	

	Concentrated milks	3.090	3.502	0.0000		1.9935	7.617	
	Buttermilk	0.441	0.500	0.0000		0.1424	0.709	
	Butter			0.2179		0.2481		
J. Berlin, 2002	Hushållsost	0.122		0.0368	3.1E-05	0.1530	1.856	2.004
M. Yan & N.M Holden, 2018	More products	1.517	1.931	0.0632	0.0049	0.0632	4.970	
A. Dalla Riva et al., 2017	Mozzarella	5.160		0.0987		0.1933	3.457	59.878
Average		***2.094***	***1.804***	***0.117***	***0.004***	***0.303***	***38.820***	***77.485***

▨ *LCA to assess the hotspot in a dairy industry, the results do not depend from the kind of dairy product.*

Table 3. LCI for the sources (energy, and additives) used both for the P-recovery technologies and for the production of the needed additives. All these data are calculated per 1 kg of struvite and for 1 kg of pure P (5.2%) in the sludge ash (K. Linderholm, 2012).

Sources	**Struvite (1kg)**
Electricity	600 KWh
Primary energy for $MgCl_2$-$6H_2O$ production	136 MJ
Energy for NaOH	2 MJ
GHG emissions for $MgCl_2$-$6H_2O$ production	10 Kg CO2eq
GHG emissions for NaOH production	0.115 Kg CO2eq
$MgCl_2$-$6H_2O$	800 Kg
NaOH	100 Kg
Sources	**Ash (19kg = 1kg pure P)**
Sewage Sludge	38 kg
Energy (pre-heating)	31 MJ
MgCl2	5 kg

Table 4. Environmental impacts related to waste and wastewater; data from literature but recalculated to the FU used in this study (1 liter of raw milk). The environmental impact categories are: GWP (Global Warming Potential), EP (Eutrophication Potential), FEP (Freshwater Eutrophication Potential), MEP (Marine Eutrophication Potential), AP (Acidification Potential), CED (Cumulative Energy Demand).

Study	Dairy Products	GWP (kg CO2 eq)		EP (kg PO43- eq)		FEP (kg P eq)		MEP (Kg N eq)		AP (kg SO2 eq)		CED (MJ)	
W. Finnegan et al., 2017	Pwd milk	6.88E-03	0.5%			1.58E-06	10%	1.18E-05	40%				
	Butter	5.71E-03	1.1%			1.50E-06		1.06E-05					
I. Djekic et al., 2014	Pst milk	2.15E-01	14%										
	UHT milk	3.29E-01	25%										
	Yoghurt	6.07E-01	29%										
	Cream	2.66E-01	24%										
	Butter	2.60E-01	27%										
	Cheese	3.69E-01	26%										
G. Mondello et al., 2018	Pecorino	3.38E-01	8.6%										
S. González-García, A. Hospido, et al., 2013	San Simon	2.73E-02	2.9%	5.45E-04	9.4%					1.82E-04	1.9%	2.55E-01	3.9%
S. González-García, E.G. Castanheira, et al., 2013	Mature Cheese			6.26E-03	77%					1.13E-02	50%		
D. Kim et al., 2013	Cheddar	1.88E-02	3.5%			1.35E-04	60%	1.95E-03	97%			1.16E-01	1.9%
	Mozzarella	2.99E-02				2.23E-04		2.45E-03				1.68E-01	
A. Dalla Riva et al., 2018	Asiago					1.60E-06	59%			8.16E-05	0.42%		
X. Vergé et al., 2013	Fluid	3.35E-03	1.6%										
	Yogurt	5.15E-02	0.7%										
A. Dalla Riva et al., 2017	Mozzarella	2.06E-02	1.5%			7.75E-06	3.3%	2.04E-04	2.1%			2.96E-01	3.2%

The light blue cell represents the percentages of the impact due to waste and wastewater, compared to only dairy process production (from the processing of the raw milk to the final product), in the other studies, the percentages are compared to the all dairy system including also the farm and the disposal of the final dairy product. The light grey means that these results are referred to wastewater management only, while white to the general waste management.

Table 5. Environmental impact results due to the P-recovery technologies per FU chosen in the LCA studies. The environmental impact categories are: GWP (Global Warming Potential), AP (Acidification Potential), CED (Cumulative Energy Demand).

Study	Functional Unit	Technology	CED kWh/FU	GWP Kg CO$_{2eq}$/FU	AP SO$_{2eq}$/FU
A. Amann et al., 2018	PE*habitant (65700 kg P)	REM-NUT®	19	4	20
		Ostara Pearl ®	2	0	1
		PRISA	2	1	2
		P-RoC	3	1	1
		AirPrex®	3	0	1
		DHV Crystallactor ®	10	3	10
		Gifhorn	40	8	74
		Stuttgart	70	10	93
		MEPHREC®	30	9	47
		Aqua Reci®	139	25	83
		PHOXNAN	91	14	118
		AshDec® (cold ash)	15	2	4
		AshDec® (hot ash)	10	1	4
		LEACHPHOS®	9	2	21
		PASCH	29	7	28
		RecoPhos®	30	5	85
		Fertilizer Industry	9	1	22
		EcoPhos®	16	3	13
		Thermphos	26	4	18
K. Linderholm, 2012	11 kg P	Pearl ®	191	23	
		Sludge	46	13	
		Ash-Dec	2107	500	
M. Svanström et al., 2017	One tonne of dry solids of undigested sludge	Incinceration+AshDec		224	1*
H. Kjerstadius et al., 2017	Management of 1 capita load of FW, BW and GW per year	Struvite precipitation		19	

The coloured cells represent the results obtained using the technologies which recover P-products from a liquid phase (light blue), from a solid phase (sludge) (yellow), and from sewage sludge ash (orange). The AP calculated for the "incineration + AshDec" technology is expressed in terms of* mole H$^+$.

3 Results and discussions

The aim of the LCA was (1) to assess the P-recovery technologies to detect which one have higher environmental impact during the recovery process and (2) how much bigger are the impacts compared to current DPWW treatment. The data calculated and described in the previous chapter have been used for the comparisons. The results of these comparisons are provided in figure 6 and figure 7.

It is important to mention that all data have been collected from the literature review from different and not necessarily comparable studies, that the P-recovery technologies were applied to municipal wastewater and not to dairy wastewater, and that results were recalculated to be valid for the chosen FUs (1 l of raw milk and 1 kg of P-product recovered).

Figure 6 shows the comparison between P-recovery technologies from different LCA studies. Results were available to allow for the technologies to be compared for three environmental impact indicators: GWP, CED and AP. The technologies have been classified in three groups, based on the flow used to recover P-products: liquid phase, sewage sludge and sewage sludge ash (SSA). Overall, the recovery of P from sludge and sewage sludge ash have higher impact compared to the recovery from the liquid phase.

Most of the methods that recover P from the **liquid phase** have a low contribution regarding CED due to the low energy and resources demand (such as acetic acid, lime, magnesium chloride, or acid sulphuric etc.). While the GWP impacts are due to the emissions from the production of the used chemicals and transports. Despite that, although struvite production from the dewatering liquid requires additional power and chemicals, there is a net reduction of GWP due to avoided N_2O emissions, lower power consumption, and reduced chemical dosing for pH control due to reduced nitrification (Z. Bradford-Hartke et al., 2015). Among the liquid phase technologies, the DHV Crystallactor® technology appears to have higher CED compared to the reference system (municipal WWT), because the replacement of the anaerobic digestion with aerobic treatment (A. Amann et al., 2018). This increment may be due to the consume of energy request for the aeration maintained throughout the oxygen supplied during the aerobic treatment. Also the increase of sewage sludge load, and its treatment to the incineration plant, that compare the others liquid phase technologies is a surplus, influences on the CED results (A. Amann et al., 2018) In addition, with the recovery from the liquid phase, the AP can achieve an improvement of the 20% compare to the reference system (A. Amann et al., 2018). Regarding the struvite recovery, performed on the digestate effluent by struvite precipitation and ammonia stripping, the GWP is due to the increase of emissions because of the chemicals and heat need for the ammonium stripper (H. Kjerstadius et al., 2017)

In the case of P-recovery from **sewage sludge** (solid phase), all the impacts are always due to energy and resource demand. In the case of the wet-oxidation process PHOXNAN, the higher CED is related to its demand for oxygen and to the disposal and treatment of waste that is produced. While in the wet chemical extraction processes (Stugggart and Gifhorn), the CED is due to a high need for chemicals that are partly energy-intensive in their production too (A. Amann et al., 2018). The kg CO_{2eq} emissions from the production of the used chemicals (Stuttgart) and the high demand for resources and fossil energy needed during the sludge mineralization (PHOXNAN) contribute to the high values of GWP (A. Amann et al., 2018). Despite that, it is important to notice also that the use of this biosolid in agricultural activities avoids kg CO_{2eq} emissions due to primarily the methane emissions from the landfill (Z.

Bradford-Hartke et al., 2015). Moreover, to these technologies is attributed a considerable increase in AP by 80% to 170%, compared to the reference system, due to the resource use in the process (A. Amann et al., 2018). The use of this biosolid in agricultural activities reduce potentially the marine eutrophication, compare to the struvite precipitation from the dewatering and brine stream (Z. Bradford-Hartke et al., 2015).

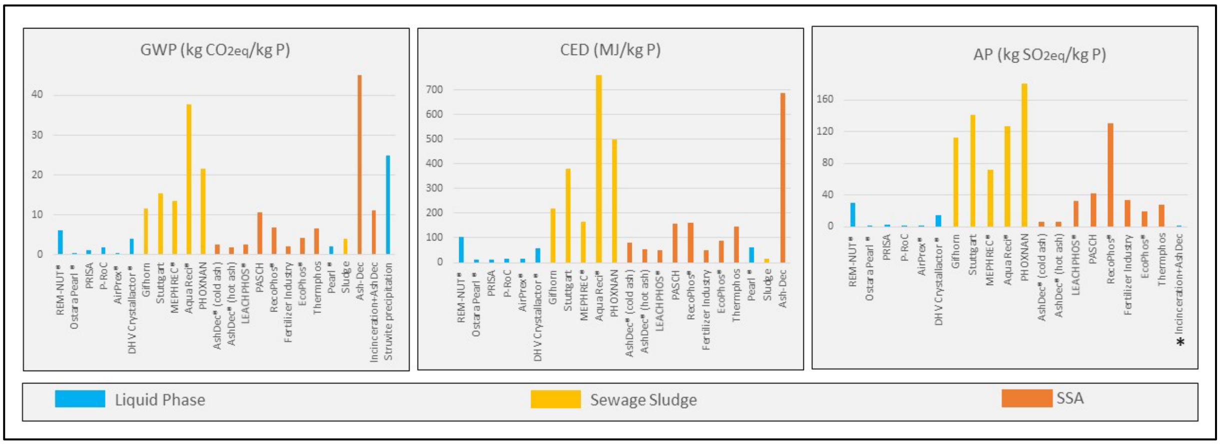

Figure 6. Comparison of the GWP, CED, and AP between the P-recovery technologies. These are the environmental impacts results for 1 kg of P-product (FU).

** The AP calculated for the "incineration + AshDec" technology is expressed in terms of* mole H^+.

Regarding the P recovery technologies for **SSA**, the increment of these impact is due to the waste treatment and disposal, such as in the case of the PASCH technology (A. Amann et al., 2018), to the incineration (M. Svanström et al., 2017) or to the heating process (K. Linderholm, 2012). These technologies, compared to the previous, require high temperatures, so the more energy requested for these processes will influence the GWP (K. Linderholm, 2012). These kinds of technologies have only a medium increase in CED compared to the reference system (A. Amann et al., 2018). The thermo-chemical AshDec process has only a low change in CED, due to the additional demand for chemicals, and in GWP, due to the operations with hot ash fares, that is slightly better due to the reduced demand for heating (A. Amann et al., 2018). On the other hand, the GWP could also increase by 3 kg $CO_{2\ eq}$, if the storage sludge process, after the digestion and before the incineration processes, is taken into consideration in the analyses (M. Svanström et al., 2017).

In figure 7, GWP results for the comparison between the P-recovery technologies and the DPWW treatment are shown. In order to do this, a recalculation was done intending to connect the process milk to the recovered P-products. For the DPWW treatment scenario, despite the results vary depending on the dairy product produced, the impacts are much higher compared to the P-recovery technologies (note the different scales for the two parts of the systems in figure 7).

The DPWW results selected for this comparison are relative only to that study that included the DPWW treatment in the LCA analysis. These LCAs on dairy industries, generally are mainly focused on the final product and not so much in the waste or by-products, or rather the DPWW treatment. So, for this comparison not enough LCIA data has been collected from the literature review.

From the results showed in figure 7, it seems clear that there may be a positive benefit involved in the application of the P-recovery technologies to the WWT. The addition of a P recovery technology can also positively influence the total impact of the dairy process. It should be noted, however, that there are limitations to this study as described earlier.

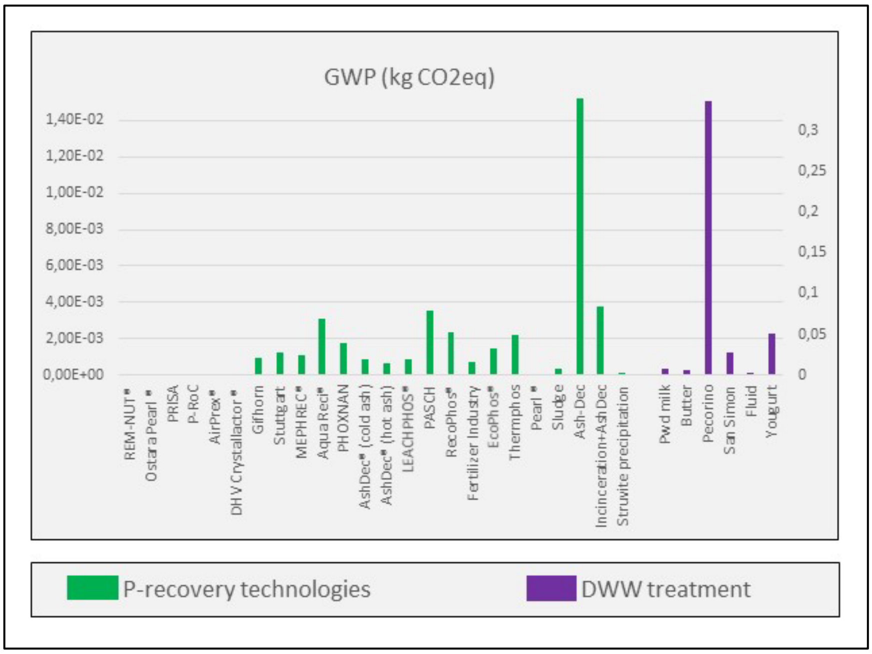

Figure 7. Comparison of the GWP between the DWW treatment and P-recovery technologies. Results calculated for 1 liter of raw milk (FU).

4 Conclusions

The purpose of the part of the LCA work described in this report was to determine the environmental assessment methodologies to be used in the REFLOW project. Two parts of the system that represent different technology contexts to be evaluated in the initial stage were (1) dairy wastewater treatment and (2) P-recovery technologies. These were explored within a literature review.

This study has identified that P-recovery technology applied to the liquid phase seems particularly promising for DWW treatment regarding a moderate environmental impact, considering the information that can be extracted from earlier LCAs.

The second major finding was that the P-recovery technologies have a higher impact compared to the DWW treatment and that efforts have to be made to, if possible, keep environmental impacts as low as possible.

An innovative approach that involves recalculating literature results for a different FU was employed to connect results from LCA studies of dairies to results from LCA studies of P recovery technologies.

The analysis was, however, limited to literature data as it was not yet possible to calculate the impact with data generated in the project. More information on the P-recovery technologies will help us to establish a greater degree of accuracy and relevance.

References

A. Amann, O. Zoboli, J. Krampe, H. Rechberger, M. Zessner, & L. Egle. (2018). Environmental impacts of phosphorus recovery from municipal wastewater. *Resources, Conservation and Recycling, 130*, 127-139. doi:https://doi.org/10.1016/j.resconrec.2017.11.002

A. Dalla Riva, J. Burek, D. Kim, G. Thoma, M. Cassandro, & M. De Marchi. (2017). Environmental life cycle assessment of Italian mozzarella cheese: Hotspots and improvement opportunities. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026657237&doi=10.3168%2fjds.2016-12396&partnerID=40&md5=1e819e74dfacde61e6825eb55fed818d

A. Dalla Riva, J. Burek, D. Kim, G. Thoma, M. Cassandro, & M. De Marchi. (2018). The environmental analysis of asiago PDO cheese: a case study from farm gate-to-plant gate. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042358643&doi=10.1080%2f1828051X.2017.1344936&partnerID=40&md5=c3446dc1cbb1bb13db5af385a355ef26

A. Flysjö, M. Thrane, & J. E. Hermansen. (2014). Method to assess the carbon footprint at product level in the dairy industry. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84883635848&doi=10.1016%2fj.idairyj.2013.07.016&partnerID=40&md5=cc7be247706edb3c9cab9f439a8183f0

A. J. Feitz, S. Lundie, G. Dennien, M. Morain, & M. Jones. (2007). Generation of an industry-specific physico-chemical allocation matrix: Application in the dairy industry and implications for systems analysis. *International Journal of Life Cycle Assessment, 12*(2), 109-117. doi:10.1065/lca2005.10.228

A. K. Slavov. (2017). General characteristics and treatment possibilities of dairy wastewater -a review. *Food Technology and Biotechnology, 55*(1), 14-28. doi:10.17113/ft b.55.01.17.4520

A.B. Heinrich. (2010). International reference life cycle data system handbook. *The International Journal of Life Cycle Assessment, 15*(5), 524-525.

C. Remy, & F. Kraus. (2019). Life Cycle Assessment of Processes for P Recycling. In H. Ohtake & S. Tsuneda (Eds.), *Phosphorus Recovery and Recycling* (pp. 59-73). Singapore: Springer Singapore.

C.E. van Middelaar, P.B.M. Berentsen, M.A. Dolman, & I.J.M. de Boer. (2011). Eco-efficiency in the production chain of Dutch semi-hard cheese. *Livestock Science, 139*(1), 91-99. doi:https://doi.org/10.1016/j.livsci.2011.03.013

C.S. Mahath, K. Mophin Kani, & B. Dubey. (2019). Gate-to-gate environmental impacts of dairy processing products in Thiruvananthapuram, India. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85055034265&doi=10.1016%2fj.resconrec.2018.09.023&partnerID=40&md5=c7f57d7d0afe59094e6b2d23277eb4d2

D. Kim, G. Thoma, D. Nutter, F. Milani, R. Ulrich, & G. Norris. (2013). Life cycle assessment of cheese and whey production in the USA. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84879505400&doi=10.1007%2fs11367-013-0553-9&partnerID=40&md5=82afff873c29e9610be7664679ce0c88

EDA. (2018). *Economic Report 2017/18*. Retrieved from http://eda.euromilk.org/fileadmin/user_upload/Public_Documents/Facts_and_Figures/EDA_Economic_Report_2017.pdf

European Commission. (2016). *Circular Economy Package*. Retrieved from https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/1-2016-157-EN-F1-1.PDF

European Commission. (2017). *Communication on the 2017 list of Critical Raw Materials for the EU*. Retrieved from https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF

F. Canellada, A. Laca, A. Laca, & M. Díaz. (2018). Environmental impact of cheese production: A case study of a small-scale factory in southern Europe and global overview of carbon footprint. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85045399760&doi=10.1016%2fj.scitotenv.2018.04.045&partnerID=40&md5=639840df29b3e23a771ffebb30dfd84f

FIL-IDF. (2010). *A common carbon footprint approach for dairy - The IDF guide to standard lifecycle assessment methodology for the dairy sector*. Retrieved from http://www.ukidf.org/documents/bulletin445.pdf

G. Doublet, N. Jungbluth, M. Stucki, & S. Schori. (2013). *Life cycle assessment of Romanian beef and dairy products*. Retrieved from http://esu-services.ch/fileadmin/download/doublet-2013-SENSE_Deliverable-2_1-LCAbeefdairy.pdf

G. M. Filippelli. (2008). The global phosphorus cycle: Past, present, and future. *Elements, 4*(2), 89-95. doi:10.2113/GSELEMENTS.4.2.89

G. Mondello, R. Salomone, E. Neri, N. Patrizi, S. Bastianoni, & F. Lanuzza. (2018). Environmental hot-spots and improvement scenarios for Tuscan “Pecorino” cheese using Life Cycle Assessment. *Journal of Cleaner Production, 195*, 810-820. doi:10.1016/j.jclepro.2018.05.078

H. Baumann, & Tillman, A. M. (2015). *The Hitch Hiker's Guid to LCA - An orientation in life cycle assessment methodology and application*.

H. C. M. Jr. Santos, H. L. Maranduba, J.A. de Almeida Neto, & L. B. Rodrigues. (2017). Life cycle assessment of cheese production process in a small-sized dairy industry in Brazil. *Environmental Science and Pollution Research, 24*(4), 3470-3482. doi:10.1007/s11356-016-8084-0

H. Herzel, O. Krüger, L. Hermann, & C. Adam. (2016). Sewage sludge ash - A promising secondary phosphorus source for fertilizer production. *Science of the Total Environment, 542*, 1136-1143. doi:10.1016/j.scitotenv.2015.08.059

H. Kjerstadius, A. B. Saraiva, J. Spangberg, & A. Davidsson. (2017). Carbon footprint of urban source separation for nutrient recovery. *Journal of Environmental Management, 197*, 250-257. doi:10.1016/j.jenvman.2017.03.094

H.A. Aguirre-Villegas, F. X. Milani, S. Kraatz, & D. J. Reinemann. (2012). Life cycle impact assessment and allocation methods development for cheese and whey processing. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84861581894&partnerID=40&md5=43c4d5064cbc13243c888bbede8626f1

I. Djekic, J. Miocinovic, I. Tomasevic, N. Smigic, & N. Tomic. (2014). Environmental life-cycle assessment of various dairy products. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84897113630&doi=10.1016%2fj.jclepro.2013.12.054&partnerID=40&md5=89796dad3bbccf5a2bf874f6af687e30

Environmental Managment - Life cycle assessment - Requirements and guidelines, (2006).

J. Berlin. (2002). Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. *International Dairy Journal, 12*(11), 939 -953. Retrieved from https://www.sciencedirect.com/science/article/pii/S0958694602001127

J.J. Schröder, D. Cordell, A.L. Smit, & Rosemarin, A. (2010). *Sustainable Use of Phosphorus*. Retrieved from https://ec.europa.eu/environment/natres/pdf/sustainable_use_phosphorus.pdf

K. Linderholm, A. M. T. J. E. M. (2012). Life cycle assessment of phosphorus alternatives for Swedish agriculture. *Resources, Conservation and Recycling, 66*, 27-39. Retrieved from https://doi.org/10.1016/j.resconrec.2012.04.006.

K. Nilsson, A. Flysjö, J. Davis, S. Sim, N. Unger, & S. Bell. (2010). Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-78149408825&doi=10.1007%2fs11367-010-0220-3&partnerID=40&md5=95a68a1c6ac57388804bd67fd183daf0

M. Svanström, S Heimersson, G. Peters, R. Harder, D. I'Ons, A. Finnson, & J. Olsson. (2017). Life cycle assessment of sludge management with phosphorus utilisation and improved hygienisation in Sweden. *Water Science and Technology, 75*(9), 2013-2024. doi:10.2166/wst.2017.073

M. Yan, & N.M Holden. (2018). Life cycle assessment of multi-product dairy processing using Irish butter and milk powders as an example. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85058487481&doi=10.1016%2fj.jclepro.2018.07.006&partnerID=40&md5=c2e4861361e399436a0847eb025022d6

N. Palmieri, M.B. Forleo, & E. Salimei. (2017). Environmental impacts of a dairy cheese chain including whey feeding: An Italian case study. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85032068757&doi=10.1016%2fj.jclepro.2016.06.185&partnerID=40&md5=4f7874f14336cda5dcbbfabc004266e6

P. Brazzale, B. Bourbon, P. Barrucand, M. Fenelon, S. Guercini, R. Tiarca, & M. Sánchez Mainar. (2019). *Bulletin of the International Dairy Federation 500: Wastewater Treatment in Dairy Processing Innovative solutions for sustainable wastewater management*.

S. González-García, A. Hospido, M.T. Moreira, G. Feijoo, & L. Arroja. (2013). Environmental life cycle assessment of a galician cheese: San Simon da Costa. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84878410026&doi=10.1016%2fj.jclepro.2013.03.006&partnerID=40&md5=de985ec3e6bcf6b0044626d73fcd3322

S. González-García, E.G. Castanheira, A.C. Dias, & L. Arroja. (2013). Environmental performance of a Portuguese mature cheese-making dairy mill. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84868674176&doi=10.1016%2fj.jclepro.2012.10.010&partnerID=40&md5=aa0c6ffefd87a3011195d59857d8dbd0

S. M. Ashekuzzaman, P. Forrestal, K. Richards, & O. Fenton. (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. doi:https://doi.org/10.1016/j.jclepro.2019.05.025

W. Finnegan, J. Goggins, E. Clifford, & X. Zhan. (2017). Environmental impacts of milk powder and butter manufactured in the Republic of Ireland. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85006356901&doi=10.1016%2fj.scitotenv.2016.10.237&partnerID=40&md5=35e420ac6d0acbb61603036d681123b3

X. Vergé, D. Maxime, J.A. Dyer, R.L Desjardins, Y. Arcand, & A. Vanderzaag. (2013). Carbon footprint of Canadian dairy products: Calculations and issues. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84882815903&doi=10.3168%2fjds.2013-6563&partnerID=40&md5=500b4ced90fa94cba4a75dd8a87760c4

Z. Bradford-Hartke, J. Lane, P. Lant, & G. Leslie. (2015). Environmental Benefits and Burdens of Phosphorus Recovery from Municipal Wastewater. *Environmental Science and Technology, 49*(14), 8611-8622. doi:https://doi.org/10.1021/es505102v