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Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy

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Abstract

The capability of Anaerobic Digestion (AD) in minimising waste and retaining the value of materials and energy within the biological and technical cycles in the Dairy Industry (DI) makes AD a critical instrument of transition to circular economy. The aim of this paper is to propose a framework and an approach for measuring the environmental performance of the anaerobic treatment of dairy processing effluents based on circular economy principles. The potential of AD to close the water, energy and nutrient circular loops is investigated together with the relevant environmental costs and benefits at different levels of the dairy supply chain. The developed methodology was based on Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) applied at three different system levels: the anaerobic digestion plant, the dairy processing facility, the entire dairy supply chain. The approach is demonstrated in a dairy facility coupled with a full-scale AD unit. The results show that the excess electricity (426 MWh/annum) and heat (1236 MWh/annum) produced from the anaerobic digestion plant cause significant reduction of the overall environmental impact of the processing facility. The recovered energy from anaerobic digestion provides 20% of the energy requirements of the factory reducing the total carbon footprint emissions by 13% compared to the baseline scenario.

Keywords: Circular economy indicators, wastewater, anaerobic digestion, dairy processing, LCA

1. Introduction

Dairy products form an essential source of daily nutrients in human diets (Weaver, 2010), whereas the dairy industry, in 2012, accounted for 13.6% of the food and drink industry turnover (Wijnands and Verhoog, 2016). Several studies discuss the need to reduce the amount of dairy products in European diet patterns (Freibauer et al., 2011), which is estimated to be beneficial both to the environment (Godfray et al., 2010) and the human health (Hawkesworth et al., 2010). However, adaptation and mitigation strategies for reduction of greenhouse gas emissions (GHG) and enhancement of environmental resilience remain main challenge for the dairy industries (Prasad et al., 2004). The production of dairy products is combination of processes, including agriculture, livestock farming, manufacturing, packaging, distribution, retail and consumption (Kirilova and Vaklieva-Bancheva, 2017). Therefore, the development of sustainable dairy value chains should take into account the reduction of the environmental impacts and cause-effect relationships within all stages of the supply chain. Dairy farms have been the focal point of environmental assessments in the dairy sector. The application of life cycle impact assessment (LCIA) has been used as a tool to facilitate the decision making in the dairy sector and increase its environmental performance. Several works have assessed the environmental impacts of the dairy sector proposing measures for the improvement of the sustainability of the dairy value chains (Battini et al., 2014; Hospido et al., 2003; Roy et al., 2009). Recovery of bioenergy (Kimming et al., 2015) and use of other renewable energy sources (Murgia et al., 2013), recycling of nutrients (Dolman et al., 2014) and wastewater treatment and valorisation (Gottschall et al., 2007), have been identified as key factors for the enhancement of the environmental profile of dairy farms. Recently, Kılkış and Kılkış (2017), developed a methodological approach for the comparison of different energy and biogas utilization schemes in a dairy farm following circular economy principles. New industrial symbiosis paradigms in Europe have demonstrated efficient management of materials, energy, water and waste flows mainly in industrial applications (WssTP, 2016), however, applications in the dairy supply chain are still premature. Monitoring of key performance indicators (KPIs) integrating environmental impact and related accountability allocation have been considered as main components for the development of an enhanced sustainability framework (Huysman et al., 2015) and as a basis for the development of circularity metrics (Linder et al., 2017).

Circular economy (CE) is gaining increased attention over the conventional “make-use-dispose” models (Ghisellini et al., 2016; Jawahir and Bradley, 2016). Fundamental principles of circular economy strategies focus on the reduction, re-use and efficiency of resources utilization (Wu et al., 2014), while boosting economic growth (Ellen MacArthur Foundation and the McKinsey Center, 2015) and therefore directly linked with sustainable waste and resource management (Blomsma and Brennan, 2017), systems thinking, re-design and “closing loops” of materials and energy flows (MacArthur, 2012). The dairy sector traditionally features circular practices and there are many examples that demonstrate the potential of circular dairy farming (Kılkış and Kılkış, 2017; Lybæk and Kjær, 2019). However, significant challenges remain to achieve a truly circular dairy sector that is regenerative and closes nutrient, water, carbon and waste cycles. The driving force for waste minimization in the dairy industry is the improved yields of product, reduced impact on the environment and lower wastewater treatment costs (Barnett et al., 2010). Waste-to-energy systems are seen as a mean to facilitate the transition to circular economy (Pan et al., 2015) and are key solutions for the mitigation of the environmental impacts in the dairy processing sector. Nowadays, with the evolving recycling technologies and solutions that are available on the market, the nutrient conversion of dairy manure and milk processing residuals is becoming more efficient and economically viable As a result, the nutrient recycling is getting momentum due to its environmental and economic benefits (Dolman et al., 2014). The Dairy sector is included in the priority list of the recent political agenda of the European Union where the circular economy is an increasing area of focus for the European businesses (EC, 2015). The anaerobic digestion (AD) has a major role in the transition to circular economy due to its capability to minimise waste and retain the value of materials and energy within the biological and technical cycles. Using the liquid by-product of anaerobic digestion to restore natural capital to soil is a step forward in finding a way to produce fertiliser from a waste resource, keeping nutrients in a cycle (Passeggi et al., 2012). Dairy factories generate significant amount of wastewater from the various processing steps (i.e. reverse osmosis for milk concentration) and during cleaning, heating, cooling or floor washing (Demirel et al., 2005). Dairy effluents constitute a good feedstock for anaerobic digestion processes, since they are characterised by significant organic and microbiological load (Carvalho et al., 2013; Karadag et al., 2015; Prazeres et al., 2012). The techno-economic viability of dairy effluents treatment by applying anaerobic digestion has been assessed in various works (Carlini M et al., 2015; Traversi et al., 2013; Demirel et al., 2006; Gelegenis et al., 2007; Zhong et al., 2015). However, these are usually are standalone studies, partially addressing individual aspects of circular economy. At the same time optimization of the operating conditions remains the main constraint for the widespread AD implementation in the dairy industry (An et al., 2010; Prazeres et al., 2012) especially without the use of other feedstock.

Most of the LCA studies in dairy sector have been focusing on the dairy farm stage (Palhares and Pezzopane, 2015; Zonderland-Thomassen and Ledgard, 2012) and only limited number of works have considered the processing stage (Vasilaki et al., 2016). There is still a gap in the literature on sound LCA based environmental impact assessment for dairy processing wastewater treatment. To the best of our knowledge, the environmental and sustainability performance of a full scale AD treatment of dairy effluents management strategy has not been systematically evaluated. The main objective of this study is to evaluate the environmental performance of the AD dairy effluent treatment and to reveal its potential to close the water, energy and nutrient circular economy loops at different levels of the dairy supply chain. More specifically, the LCA was applied to assess the environmental performance of the AD, as well as its benefit and costs ratios at each level. The approach was applied to a dairy processing facility coupled with full-scale high-rate liquid AD unit treating the dairy processing effluents, located in South West of the UK. The novelty of this study is to translate the LCA and MFA results into suitable circular economy metrics for measuring the effectiveness of AD wastewater treatment on circularity performance, both in terms of efficiency and scale. The findings of such analyses will facilitate decision makers and managers towards improving sustainability of dairy industry.

2. Materials and Methods

CE is often associated with eliminating waste and closing the technological and biological material loops. Figure 1 illustrates the ability of AD treatment to increase the circularity potential by reducing the direct environmental pressure to receiving waters and valorise the embedded resources in the dairy effluents by closing the water, energy and nutrient loops at different stages of the dairy supply chain. A linear model of the water usage in dairy factory would follow the take, make dispose concept, where water is taken directly or indirectly (by a public drinking water system) from the nature and after its use the generated wastewater is discharged untreated into receiving water bodies. The latter results in release of direct emissions to water bodies, which can cause eutrophication and have other adverse effects on the ecosystem. Nowadays, water use industries should meet certain regulation and legislation standards for discharging their effluents either directly into the environment or into a public sewer. In this sense, the pre-treatment/treatment of the effluents of a dairy factory can be considered already as a step towards circularity depending on the water quality level and further appropriate use of the treated effluents. Therefore, the scenario in which the wastewater is discharged directly into the environment (linear model) is more suitable to be used as Baseline (reference point) to which all circularity scenarios are relatively assessed. (Figure 1).

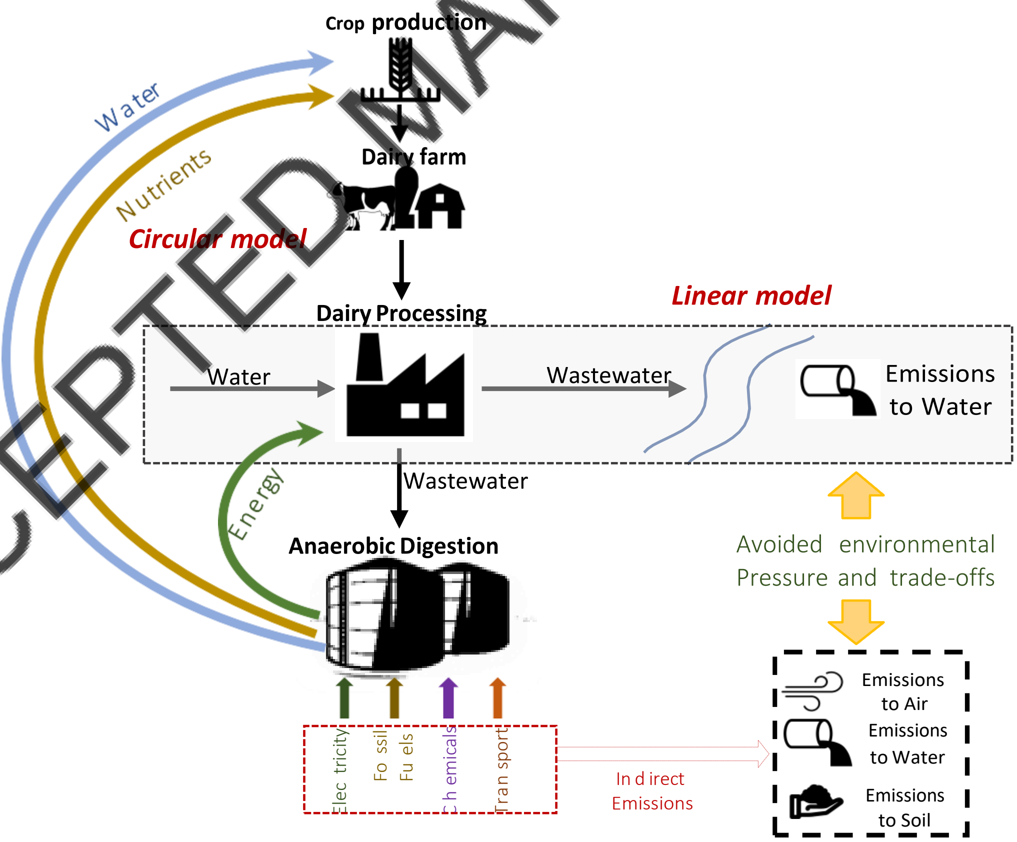

Figure 1 Circular economy loops in the dairy supply chain

The anaerobic digestion process enables the recovery of embodied resources from the dairy wastewater that can be recycled in a closed loop fashion at various stages of the supply chain. However, focusing ultimately on closing the water, material and energy loops can result in bigger externalities and even lead to negative net environmental performance. The LCA has been recognised as a valuable tool to capture these trade-offs and justify the overall net environmental impact of a system change. Therefore, the proposed methodology follows the key elements of the LCA, which generally consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment and interpretation of results (ISO 14040, 2006). The results of the LCA identify the processes that have the highest impact in the product lifecycle and facilitate the selection of suitable measures for the overall environmental impact reduction. Although, the conventional LCA includes credits for recovered materials or substituted resource inputs, it does not provide suitable and meaningful interpretation of the results from circular economy perspective. Therefore, in the proposed methodology the LCA has been aligned to the circular economy approach by including additional means of interpretation and two circularity indicators expressing the material and environmental circularity performance.

2.1. System description

The studied dairy processing facility is located in the South West of United Kingdom. The raw milk is sourced from local community dairy farms within 25 miles distance from the facility. The dairy farms vary in size from small family farms with 80 cows to larger farms with up to 400 cows. The cows are fed with grass during the summer months, while in the winter they are fed mainly with silage and cereals. The dairy processing company processes about 42 million litres of milk annually and produces various fresh and cultured dairy products for food manufacturers and service operators in the UK. It generates about 80,000 m^3 of wastewater annually from various processing stages, such as milk receiving/storage, pasteurisation, homogenisation, separation/clarification, cheese/butter/milk making, packaging and during cleaning, heating/cooling or floor washing. The dairy plant wastewater contains milk components, and acid and alkaline detergents used in the equipment cleaning. There are two wastewater streams leaving the dairy processing facility – 1) trade effluent from spillages and wash-water rinses; and 2) wastewater generated during soft cheese production (permeate of milk ultrafiltration). The permeate is characterised by high chemical oxygen demand (COD) load ranging from 40.4 to 64.8 g/L, whereas the average COD concentration of the trade effluent is 15.0 g/L. The wastewater streams generated from the dairy facility are stored in two equalization tanks and the mixed flow is fed to the AD reactor resulting in 21.1 g/L COD and 0.4% Total Suspended Solids (TSS) in the feedstock. Thus, the AD operates with 3.29 kg COD/m^3·d Organic Loading Rate (OLR) and average hydraulic retention time (HRT) of 6.90 days.

2.2.System boundaries

System boundaries are usually defined according to the goal of the study and include the relevant processes in the product system (ISO 14044, 2006). However, within the context of circular economy the boundaries are dependent also on the upstream and downstream processes. This is because the resource and energy recovery loops are crossing different levels in the supply chain in an open loop or closed loop fashion. Therefore, in order to better assess the AD circularity performance , three levels of system boundaries have been defined**: Level 1:** AD treatment plant; **Level 2:** Dairy processing factory; and **Level 3:** The entire dairy supply chain – from the raw inputs in the farm stage to the dairy products distribution to the end customers (Figure 1). The analysis at Level 1 aim to evaluate the environmental efficiency of the AD unit, while at Level 2 and Level 3 reveal the scale of AD circularity improvements at dairy factory and supply chain level.

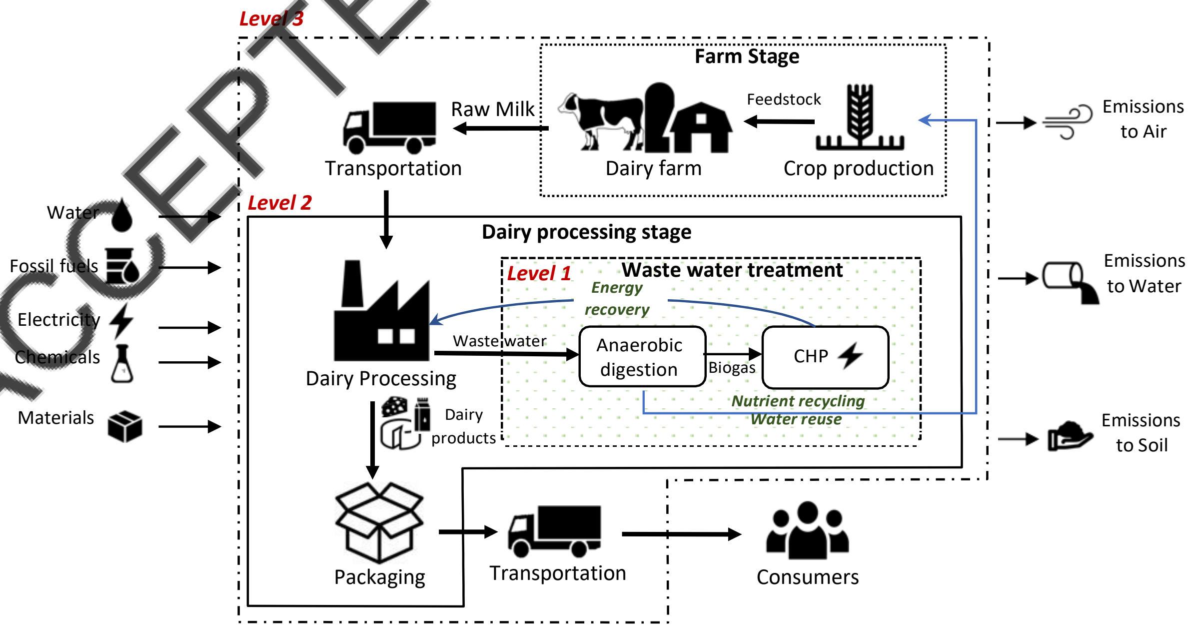

Figure 1 Multilevel system boundaries within the dairy supply chain

2.3.Definition of functional unit (FU)

The main purpose of the functional unit is to quantify the performance characteristics for a target flow in the system and to provide a reference to which all inputs and outputs of the system are normalised (ISO14044 and ISO 14040, 2006). In Level 1, the m^3 of wastewater on the input of the AD was selected for a FU as a common choice in most of the LCAs applied on wastewater treatment processes (Berlin, 2002; Dolman et al., 2014; Salou et al., 2017). On a dairy factory or farm level, the most widely used functional unit is based on input mass/volume of the raw milk or focuses on the nutritional / economic aspects of the final dairy products (Cederberg and Mattsson, 2000; Flysjö et al., 2011). For the analysis at level 2 and level 3, FU of 1 kg of fat and protein corrected milk (FCPM) was chosen as recommended by the International Dairy Federation (IDF) guidelines (IDF, 2015). However, since the calculation of FCPM using the standard fat (4%) and protein (3.3%) equals ~1 kg of raw milk, for simplicity, the “1 kg of processed raw milk” was used.

2.4. Life Cycle Inventory analysis

Primary data were collected from the dairy processing company about the operations of the installed AD plant, including: water, chemicals, energy consumption, energy generation, transport, and digestate management. The type of data used for the LCA were based on experimental data and the measurement records of main parameters (COD, TSS) (ii) complete mass balance of the process, and (iii) and data extracted from the relevant literature about the parameters related to emissions characterization. The construction of the AD plant has proven to have a minor contribution to total environmental impact thus the construction stage of the plant has not been taken into account in the analysis (Mezzullo et al. 2013). **Figure 2** shows the material and energy flows of the treatment of dairy effluents. The characteristics of the treated effluent are shown in **Table 1.** The annual capacity of the mesophilic AD unit is 70,000 m^3 whereas currently the average influent to the reactor is 121.3 m^3/day. The operating parameters of the system are summarised in **Table 2**.

The produced biogas from the AD plant is about 0.35 m^3 CH_4/kg COD_{rem} and consists of 64% CH_4 and 36% CO_2 and is lead to a combined heat and power (CHP) engine where 2,258 kWh/day electricity on average is generated. The CHP unit has 105 kW electrical output and 32% electrical efficiency. The majority of the electricity generated (about 62%) is used for the operation of the AD plant, while the remaining electricity is used to cover the energy needs of the dairy facility or fed to the national grid. The AD effluent is characterised by 15.5 g/L COD and 1.3% TSS (average values).

The digestate is pumped out of the AD reactor into two Dissolved Air Flotation (DAF) units where it is thickened and polished, resulting into about 140 m^3/day of treated effluent with 276 mg/L COD concentration. Approximately 92.5% of the thickened digestate is recirculated to the reactor and 7.5% is further thickened to a screw press (18% TSS).

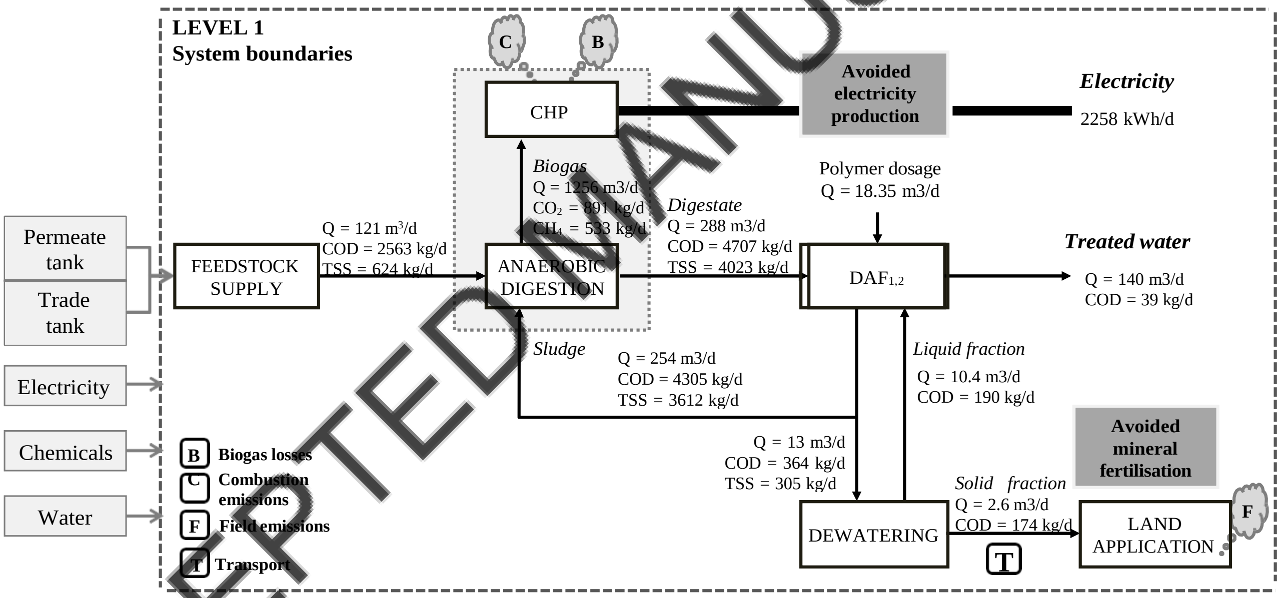

Figure 2. Flowchart of the anaerobic digestion plant treating dairy processing wastewater

Table 1. Summary of input and output parameters in dairy AD unit.

Parameters	Units	Permeate	Trade	Effluent
Wastewater flow	m^3/d	24.0	97.0	140
COD	g/L	48.4	14.4	0.28
TSS	%	0.37	0.55	-

Table 2. AD operating parameters.

Parameters	Units	Value
HRT	Days	6.7
OLR	Kg COD/m^{3}day	3.9
SRT	Days	36
T	°C	30.7

The avoided impacts from the substitution of mineral fertilisers with the organic fertiliser, generated from the AD were calculated based on the IPCC guidelines (IPCC, 2006). The electricity and heat produced from biogas combustion in the CHP unit was assumed that substitutes an equivalent energy amount of electricity and kerosene used in the dairy processing facility. The carbon emissions generated during the valorisation process of the produced biogas from the AD have not been included in the analysis, since the biogas is derived from organic waste streams. Thus, it does not add to the carbon dioxide load in the atmosphere since the CO_2 emissions produced during combustion of biogas are offset by either the carbon dioxide consumed by the biomass or by the avoided fugitive methane emissions.

In the expanded system boundaries (Level 2 and Level 3) the dairy processing stage has been considered as a "black box" representing an aggregation of processes, including the wastewater treatment stage. The total input and output energy and material flows for the operation of the dairy facility were collected from the dairy company. The transport emissions for supplying raw milk, packaging materials and the distribution of the dairy products were calculated based on the weight and the average distance to the providers and retailers respectively. Secondary data obtained with SimaPro from Ecoinvent® databases were used for the farm stage and all other upstream process to estimate the environmental impacts related to the intermediate inputs from the technosphere.

The global inventory data is given in **Table 3**.

Table 3. Global annual inventory data of material and energy flows for the dairy supply chain

Inputs from technosphere	Amount	Unit	Data source

Raw milk	42,000,000	kg/year	Primary data: Dairy factory
Total Water Usage	12,450	m3/year	
Chemical Usage			Primary data: Dairy factory
Dairy processing			
Disinfectant: mainly PAA	51,125	kg/year	
Detergent	4,200	kg/year	
Alkaline detergent: NaOH and KOH	152,010	kg/year	
Acid: nitric and phosphoric acid	8,470	kg/year	
Enzyme: protease, lipase	11,210	kg/year	
Wastewater treatment			
Flocculant (polyvinylvhloride)	27,000	kg/year	
Calcium carbonate	1,000	kg/year	
Iron (III) chloride, without water,	24,000	kg/year	
Sodium Hydroxide	36,000	kg/year	
Energy use			Primary data: Dairy factory
Dairy processing			
Fuel (Kerosene/light oil)	450,934	kg/year	
Electricity	3,687,989	kwh/year	
Wastewater treatment			
Electricity	398,652	kwh/year	
Packaging materials			Primary data: Dairy factory
Card Sleeve	18,942	kg/year	
Cardboard Divider	2,200	kg/year	
Cardboard Outer	15,330	kg/year	
Paper Label	36,546	kg/year	
Plastic Bucket	342,142	kg/year	
Plastic Carton	3,978	kg/year	
Plastic Film	12,860	kg/year	
Plastic HDPE(2) Bottle	28,188	kg/year	
Plastic HDPE(4) Lid	2,619	kg/year	
Plastic label	643	kg/year	
Plastic Lid	107,350	kg/year	
Plastic Liner	22,330	kg/year	
Plastic Pot	9,156	kg/year	
Transportation			Primary data: Dairy factory
Distribution of products	7,302,050	t-km	
Average Distance to main distribution points	310	km	

Total weight of generated products	23,555	t	
Chemical/ingredients inputs	81,725	t-km	
Average distance from providers	360	km	
Packaging materials	251,755	t-km	
Average distance from providers	418	km	
Raw milk input	840,000	t-km	
Average distance from providers	20	km	
Waste disposal	40,250	t-km	
Average distance to landfill	50	km	

Outputs to technosphere	**Amount**	**Unit**	**Data source**
Avoided energy production			
AD Electricity Generation from CHP	824,039	kWh/year	Primary data: Dairy factory
AD Heat Generation from CHP	1,236,000	kWh/year	Primary data: Dairy factory
Avoided fertiliser production			
Generated sludge	805,000	kg/year	Primary data: Dairy factory
N fertiliser substitution	397	kg/year	Vadenbo et al. 2017
P fertiliser substitution	2287	kg/year	Vadenbo et al. 2017
Land application emissions of the recovered fertilizer			
Direct N2O	3.97	kg N-N$_2$O/year	IPCC 2006 guideline
Indirect N2O (atm. deposition)	0.79	kg N-N$_2$O/year	
Indirect N2O (Leaching)	0.89	kg N-N$_2$O/year	
Indirect NO3 (Leaching)	119.10	kg N-NO$_3$/year	EMEP/EEA 2016 guideline
NH3 emissions	26.16	kg N-NH$_3$/year	
NO emissions	7.41	kg N-NO/year	
Phosphorus leached to ground water	0.07	kg P/ha*year	SALCA emission models
Phosphorus lost by runoff	2.13	kg P/ha*year	
Phosphorus emitted through erosion to rivers	0.0008	kg P/ha*year	
Waste			
Wastewater	80,346	m3/year	Primary data: Dairy factory
Packaging waste	58.4	t	

The Life Cycle Impact Assessment (LCIA) was conducted following the ReCiPe Midpoint (H) 1.12 method (Goedkoop et al., 2009). Based on the nature of the system eight environmental impact categories were selected: climate change (CC), ozone depletion (OD), freshwater eutrophication (FE), ionising radiation (IE), agricultural land occupation (ALO), water depletion (WD), metal depletion (MD) and fossil depletion (FD). The software SimaPro v8.0.5.13 was used for the computational implementation of the inventories.

2.5.Circularity performance assessment

The potential of circularity and the benefits of the AD treatment in dairy sector have been highlighted in a number of studies in the dairy sector (Demirel et al., 2005; Malaspina, F. et al., 1996; Strydom JP et al., 1997). However, although there are several comprehensive sets of CE performance indicators on national and regional level (EASAC, 2016), to date there is still no standardized and well-established method to measure the circular economy performance on product level.. Quantitative indicators are essential to evaluate how well an organization or product system performs in relation to the CE principles. One of the main challenges in evaluating circularity is the selection of units that allow integration of the different circularity aspects into a single value of circularity. In this paper, two dimensionless circularity metrics based on MFA and LCA have been proposed to evaluate the material and environmental circularity performance of the AD solution.

Material circularity performance indicator (MCPI)

The material circularity performance metric is based on the Demand Minimisation Index (DMI) suggested by Agudelo-Vera et al., 2012 (Equation 1) which enables to assess to what extent the baseline demand of resource or energy flow is reduced at the level of the actual closing of the circularity loop. This results in a value between 0 and 1, where 0 means that there is no reduction in the demand and 1 means that the whole demand is covered.

(1)

$$MCPI = \frac{Baseline\ demand - Minimised\ demand}{Baseline\ demand} \qquad (2)$$

Environmental circularity performance indicator (ECPI)

The main purpose of the LCA is to quantify both positive and negative environmental impact of a product system throughout its life cycle. Therefore, it is often considered as complementary and in line with the circularity assessment. However, the LCA is based on the conventional “cradle to grave” approach and even that it includes credits for the displaced materials and resources, its interpretation is not fully in consonance with circular economy concept. From LCA point of view, the anaerobic treatment is considered ultimately as an end of life solution ("...grave"), focused on the reduction of direct environmental pressure from the generated dairy effluent. On the other hand, the circular economy is based on the "cradle to cradle" principle, which shifts the perception of wastewater from waste flow to a source of valuable materials (Zijp et al., 2017) where the AD is seen as resource recovery solution ("…cradle"). Therefore, from circular economy perspective, the AD treatment can be defined as a multifunctional process with two main functions with relevant "environmental benefits": 1) treatment of the wastewater to reduce direct environmental pressure to the water body (primary function); and 2) recovery of energy and valuable resources which brings indirect environmental benefits as a result of the avoided virgin material and energy sources (secondary function). However, to fulfil these two functions the AD requires the use of external resources such as energy, water and chemicals for its operation, which on the other side are associated with negative indirect environmental impact – "environmental costs" (Fig. 1). In this sense, one can argue that an end of life solution is more circular when its overall "environmental benefits" outweighs its "environmental costs" including the indirect and direct impact generated within the foreground and background systems at the level where the circularity loops are closed. Therefore, an Environmental Circularity Performance Indicator (ECPI) based on the ratio of the total environmental benefits and costs is proposed to measure the circular environmental performance. The ReCiPe Endpoint (H) 1.12 method has been applied in order to normalise and aggregate both the direct and indirect environmental impact categories into one single score indicator. The ECPI indicator for the circularity performance of the AD is defined according to Equation 2:

$$ECPI_{AD}^{L_{\mathrm{i}}} = \frac{EB_{direct}^{L\mathrm{i}} + EB_{indirect}^{L\mathrm{i}}}{EC_{direct}^{L\mathrm{i}} + EC_{\mathrm{i}direct}^{L\mathrm{i}}}$$

,where

$EB_{direct}^{L\mathrm{i}}$ is the direct (foreground) environmental benefit i.e. the reduced environmental pressure (e.g. avoided eutrophication, emissions from sludge disposal);

$EB^{Li}_{indirect}$ is the indirect (background) environmental benefit i.e. avoided environmental impact from recovered products (e.g. energy, fertilisers);

EC^{Li}_{direct} is the direct (foreground) environmental cost (e.g. emitted CH_4 and CO_2 emissions);

$EC^{Li}_{indirect}$ is the indirect (background) environmental cost (e.g. embodied emissions to the resources used, transportation)

L_i, is the level at which the environmental assessment is performed

The indicator provides an aggregated metric of the environmental performance of a circular solution whereas an output value less than 1 indicates a negative environmental circularity performance and more than 1 indicates a positive performance.

2.6 Sensitivity analysis

The inherent uncertainties regarding the method used, the initial assumptions and the quality of the data could affect the results. In order to address this issue, a sensitivity analysis of the main inputs has been conducted. For this purpose, a ± 10% change from the average of the main input parameters has been simulated and the relevant effects on each impact category were calculated, assuming all other factors remained fixed at their mean level. The sensitivity results aim to reveal the parameters that contribute the most to the selected impact categories.

3. Results and discussion

3.1. Environmental assessment results

The characterisation impact assessment results for the three sub-system boundary levels are shown in Table 1. The negative values at Level 1 indicate net positive environmental impact for these impact categories meaning that the environmental benefits outweigh the environmental costs.

Table 4 Characterisation impact assessment results

Impact Category	Abbreviation	Unit	Level 1	Level 2	Level 3
			FU 1 m3	*FU 1 kg FPCM*	*FU 1 kg FPCM*
Climate change	CC	kg CO_2 eq	-15.1	0.0991	1.92
Ozone depletion	OD	g CFC-11 eq	-4.50E-03	2.32E-05	1.06E-04
Freshwater eutrophication	FE	g P eq	-4.28	0.0240	2.76
Ionising radiation	IR	kBq U235 eq	-10.25	0.0242	0.0792
Agricultural land occupation	ALO	m^2a	-1.96	0.0192	1.44
Water depletion	WD	m^3	0.415	1.11E-03	0.0404
Metal depletion	MD	g Fe eq	3.1	2.30	61.9
Fossil depletion	FD	kg oil eq	-13.7	0.0506	0.241

Environmental performance assessment of the AD system (Level 1)

Error! Reference source not found. shows the relative contributions to the impact categories of the environmental performance of the anaerobic digestion system. The environmental benefits resulting from the reduced N and P discharge to the receiving water bodies, valorisation of heat, energy and digestate that is applied as fertiliser are shown in the figure with negative contributions. The AD process for the treatment of the dairy effluent results in environmental benefits for most of the impact categories. The largest environmental benefit is in the eutrophication impact category (around 80%) due to the of N and P removal in the AD treatment process. Approximately 48% of the generated electricity is utilized for the operation of the anaerobic digestion facility (about 399 MWh/annum), while the surplus electricity (426 MWh/annum) is used to cover the dairy processing facility electricity needs. In the dairy processing facility, a kerosene boiler is used for heating purposes; thus, the CHP heat replaces equivalent heat produced from the boiler (kerosene). The electricity produced from the combustion of the biogas, is mainly responsible for the environmental benefits of the AD process with overall contribution ranging from 20% to 70%, for all impact categories. Additionally, the avoided impacts from the utilization of the heat produced in the CHP unit contribute to OD and FD impact categories (relative contributions equal to 41% and 32% respectively). On the contrary, the chemicals used in the AD plant are mainly responsible for the negative environmental impacts for most of the impact categories and particularly for the OD and WD (24% and 64% respectively).

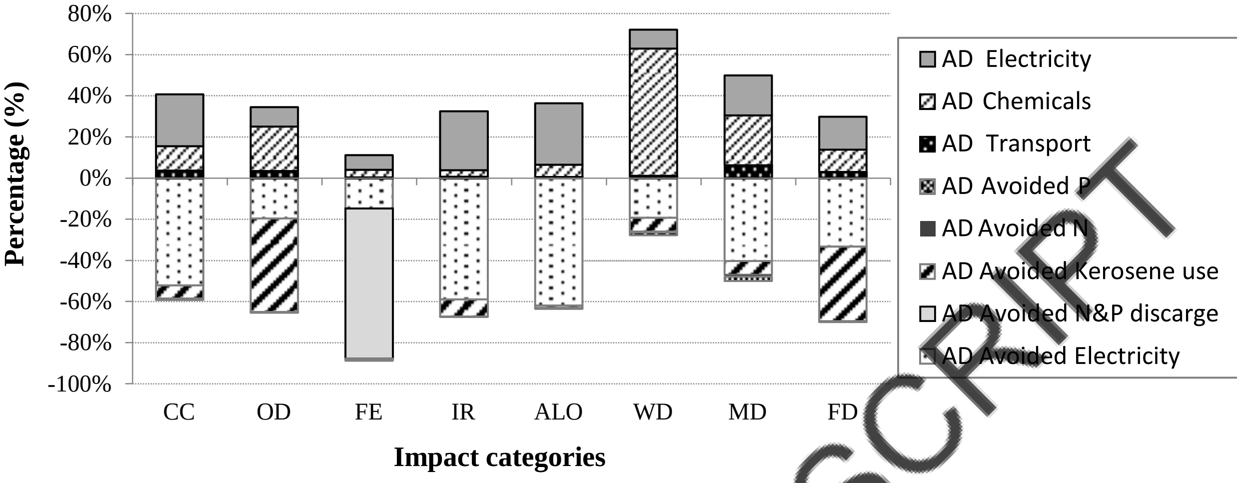

Figure 3: Relative contributions to each impact category from different activities involved in the level 1 assessment.

There are only few studies available on the life-cycle based environmental analysis of AD process in the UK using waste as feedstock, with limited information on the operating characteristics and the mass balances of the systems. Whiting and Azapagic (2014), assessed the environmental impacts using the CML 2011 method of a UK AD-CHP plant operating with a mix of different agricultural wastes. Similarly, Styles et al. (2015) implemented CML 2010 method to determine the environmental impacts of AD installations in UK dairy farms. However, the results of the current work cannot be directly compared with the cited studies since different impact assessment methodologies or functional units were used. Nevertheless, all studies have concluded that the displacement of kerosene with the heat from AD contributes significantly to mitigate CO_2 emissions and fossil fuel depletion leading to an overall net negative climate change impact.

Environmental performance of the dairy processing facility (Level 2)

The expansion of the system boundaries to the dairy facility (level 2) provided insight on the most significant contributors to its environmental profile, shown in Error! Reference source not found.. It can be seen that that the avoided direct eutrophication potential is almost equal to the indirect eutrophication associated with the resources used in the dairy processing. The excess energy produced from the anaerobic digestion unit, is equal to 188 ton of CO_2eq savings in the facility per annum. Benefits are also observed in IR, MD and FD impact categories (19%, 14% and 12% respectively).

One of the most significant contributors to the majority of the impact categories is the energy requirements of the dairy facility. About 3687 MWh of electricity is required annually for the processing of the dairy products, whereas ~450 ton of kerosene are used for the heating requirements in the processing stages. The electricity and fossil fuels consumption in the dairy plant are equal to 1.25 kWh/L and 1.93 kWh/L of milk processed respectively. A wide range of electricity consumption has been reported for the European dairy sector based on different dairy products ranging from 0.15 – 2.5 kWh per kg of liquid milk processed for the production of milk and yoghurt products to 0.08 – 2.9 kWh per kg of liquid milk processed for the production of cheese products (Expo and Sevilla, 2003). In terms of fossil fuels consumption, the reported values range from 0.18 – 1.5 kWh per kg of liquid milk processed for the production of milk and yoghurt products, to 0.15 – 4.6 kWh per kg of liquid milk processed for the production of cheese products. Therefore, the energy requirements of the examined dairy facility (mixture of milk, cheese, yoghurt products) are moderate compared to the respective ones of the European dairy industry.

Additionally, the packaging materials are identified as ‘hotspot’ in the majority of the categories, especially for ALO (relative contribution equal to ~69%) and OD (relative contribution equal to ~50%). The packaging is responsible for around 30% of the carbon footprint emissions in the dairy facility. The environmental impacts of packaging in dairy products have also been identified as an environmental hotspot in other research works (González-García et al., 2013a; Vasilaki et al., 2016). Bio-based packaging materials (i.e PLA, polyhydroxyalkanoates (PHA) etc.) have been proposed in the literature as alternatives to conventional synthetic polymers towards the mitigation of the environmental impacts of food packaging (Licciardello, 2017).

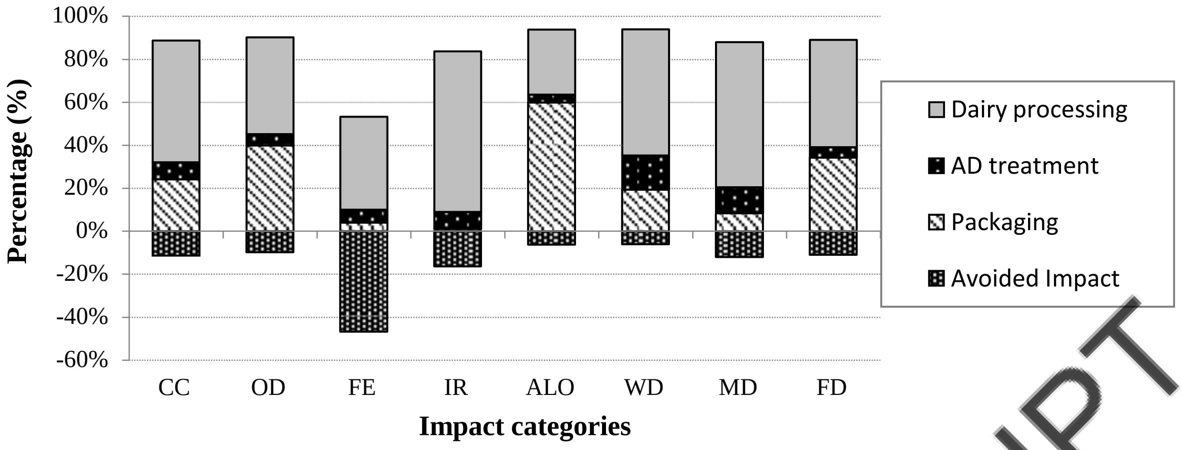

Figure 4: Relative contributions of activities involved at level 2 to each impact category

Direct water consumption in the plant mainly affects the WD impact category (20% relative contribution) with 4.2 L water consumed per L of milk processed. According to the European Commission Directorate (Expo and Sevilla, 2003), water consumption for the processing of milk and yoghurt products, varies from 0.8 to 25 L/kg of processed milk whereas the range for cheese products is even higher and equal to 1-60 L/kg of processed milk. Therefore, water consumption in the processing plant is relatively low compared to European average.

Environmental assessment of the entire dairy supply chain (Level 3)

The relative contribution of each sub-system on the entire dairy supply chain is shown on **Error! Reference source not found.** (dairy farm, processing plant, anaerobic digestion system) to the examined impact categories. The production of raw milk is the most significant contributor to all impact categories examined and almost the sole contributor for ALO, FE and WD (relative contribution equal to 96-99%). These findings correspond to the outcomes of other studies. Palmieri and Salimei (Palmieri et al., 2017) examined the effect of different cow feeding strategies on the environmental profile of cheese products and they demonstrated that irrespectively of the feeding strategy, raw milk is the main contributor of the environmental impacts in the dairy value chains. Previous studies assessing various dairy products have stressed the significance of the farm system (Fantin et al., 2012; Finnegan et al., 2015; González-García et al., 2013b) with contributions to the total carbon footprint of the products ranging from 81% to 93%. Even though the environmental impacts related to the production of raw milk affect significantly the profile of the dairy end-products the dairy processing facility contributes significantly to OD, IR, FD, MD and CC impact categories (relative contributions equal to 12%, 34%, 13%, 3% and 4% respectively). Significant environmental impact is attributed also to the distribution of the final products. Dairy products' distribution to retailers accounts for 6% of the total carbon footprint and 17% of the OD, which is attributed to the GHG emissions emitted from the truck's fuel combustion and the long distribution routes.

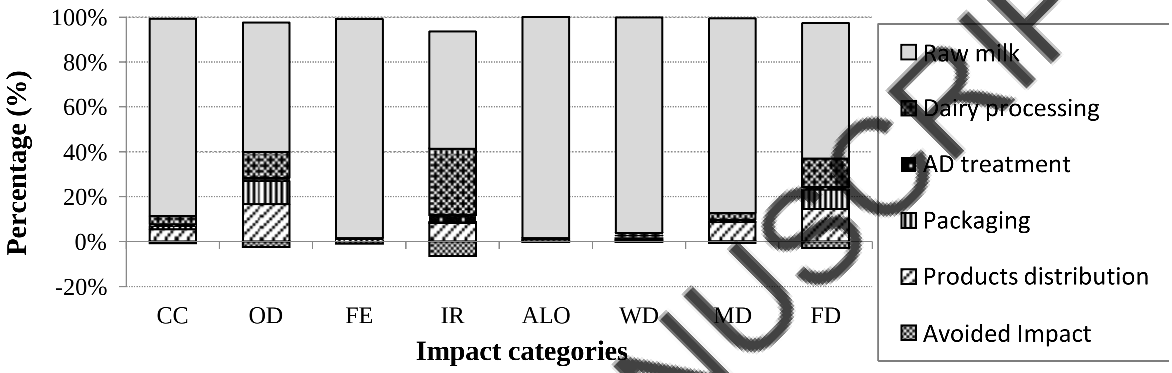

Figure 5 Relative contributions of various activities involved at level 3 to each impact category.

Sensitivity analysis

Fig. 6 shows the result of the sensitivity analysis performed regarding the main resource inputs (chemicals, transportation and energy) in the dairy supply chain and their endpoint impact at each system level. The results are based on 10% increase and 10% decrease in the average values of the individual input parameters. The energy has significant impact at all system levels with main contribution on Level 1 and Level 2. This is interpreted by the high dependency of dairy facility processes and AD on energy use (electricity and kerosene). Transportation is the major contributor to Level 3 with highest impact in the whole dairy supply chain.

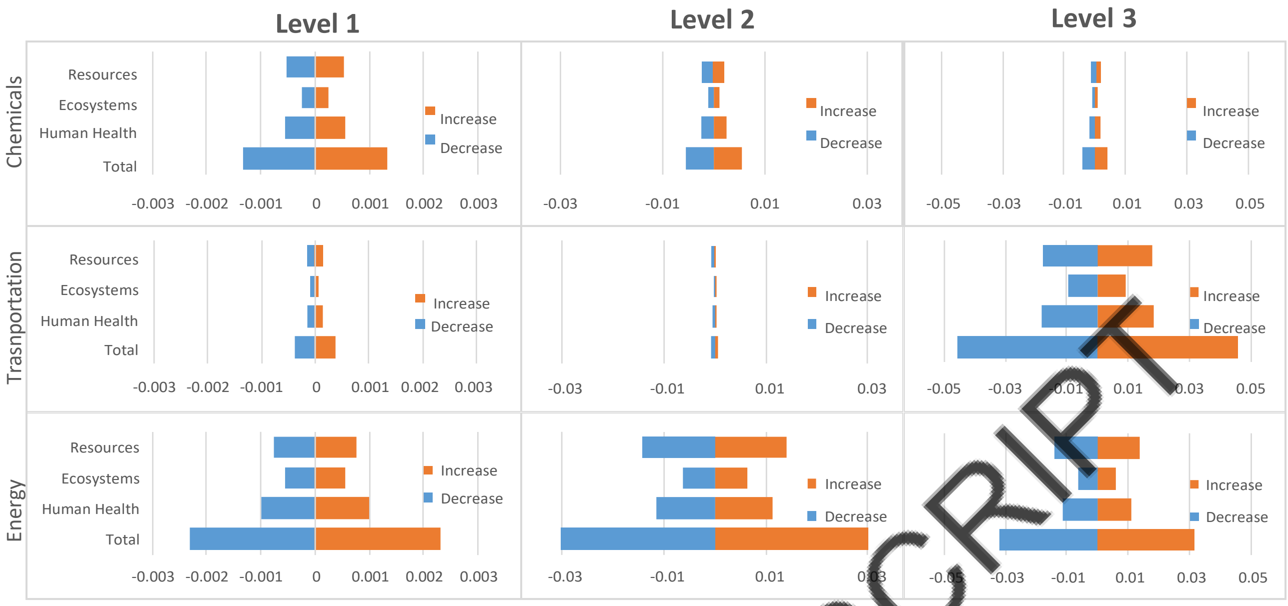

Figure 6 Multilevel sensitivity analyses

3.2. Circularity performance evaluation

3.2.1. Material circularity

Material circularity is a key element in the circular economy, which addresses the challenges of resource scarcity, whilst delivering the same functionality. Within this context, AD has many advantages, since apart from its primary function to treat the wastewater and remove organic content, it also produces a valuable by-product (biogas), that can be recovered and utilized as a fuel; and generate sludge that can be utilised as fertilizer. The recovered N and P fertilizers are key elements in the biological nutrient cycle of the circular economy, especially the P, which is a scarce and finite resource. In this case, it is considered that the recovered energy and materials from AD are recycled in a closed loop to the dairy factory (Level 2) and to the farm stage (Level 3). It is assumed that the solid fraction of the digestate is applied directly to the land as a fertiliser for crop production to feed the cows. As described in the methodology section, the material circularity indicator (MCPI) was calculated based on the demand minimization index taking into account the actual reduction of the baseline demand at the level that the circular loop is closed. Table 5 presents the MCPI results that related to the valorisation of the recovered energy and nutrients at the relevant system level; level 1 has not been considered here as it represent the AD solution itself. The water pathway has not been included in the analysis, since the irrigation of pastures is not considered to be economically viable in the UK. The MCPI shows that the energy obtained from the anaerobic treatment leads to a reduction of 11.55% for electricity and 26.61% for kerosene consumption of the plant. At level 3 the nutrients derived from the dairy sludge account for about 0.033% N and 5,41% P fertilizer displacement at the farm. The MCPI indicators show that the AD solution has a considerable potential towards a more circular management in the dairy supply chain by minimising the baseline use of raw resources and providing a more self-sustaining system.

Table 5 Material circularity performance indicator results

System boundary level at which the CE loop is closed	**Resource**	**Baseline Demand**	**Minimised demand**	**MCPI**	
				[-]	[%]
Level 2	**Energy**				
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Kerosene [kg]	450,934	330,934	0.266	26.61%
Level 3	**Nutrients**				
	N fertilizer [kg]	1,214,400	1,214,003	0.00033	0.03%
	P fertilizer [kg]	42,240	39,953	0.054	5.41%

3.2.2. Environmental circularity

When applying the LCA following the circular economy mind-set it is important, as mentioned above, to consider very carefully the system boundaries of the study. A standard application of the LCA and definition of system boundaries may not properly account for the environmental effects of the recovered materials and resources that cross the system boundary and are utilised in the upstream or downstream of the system or by other products or processes. A comprehensive LCA study that complies with the circular economy principles should extend the system boundary to the level that the circularity loops are closed considering processes and products beyond the initial life cycle, in order to correctly evaluate the circularity performance in the environmental domain for each potential scenario. Table 6 demonstrates the application of this approach to the AD treatment solution based on the LCA analysis performed following the Endpoint (H) 1.12 method. Although the endpoint environmental assessment method is associated with increased uncertainty of the results, in this case it is considered reliable enough to best represent the aggregated environmental cost-benefit ratio.

Table 6 Environmental circularity performance indicator calculation

System boundary level at which the CE loop is closed	Damage Category	Environmental benefits $EB^{Li}_{direct} + EB^{Li}_{indirect}$	Environmental costs $EC^{Li}_{direct} + EC^{Li}_{idirect}$	ECPI [-]
Level 2 (Energy CE pathway)	Human health [kPt]	23.55	17.04	1.38
	Ecosystems [kPt]	13.16	8.67	1.52
	Resources[kPt]	32.34	14.39	2.25
	Total [kPt]	**69.04**	**40.10**	**1.72**
Level 3 (Nutrient CE pathway)	Human health [kPt]	6.63	1.68	3.95
	Ecosystems [kPt]	1.96	0.87	1.05
	Resources [kPt]	0.35	1.65	0.21
	Total [kPt]	**8.94**	**4.20**	**2.13**

The ECPI indicators represent the environmental benefit-cost ratio performance for the energy and nutrient circularity loops at the relevant system level. At Level 2, the ECPI shows that the AD treatment has a positive environmental circularity performance in all damage categories varying from 1.38 to 2.25. The single score ratio of the total impact result in a value of 1.72 meaning that the overall environmental benefits are ~1.7 times higher than the related environmental costs induced from the AD operation. At Level 3, a clear trade-off between the damage categories is observed. In Human health category the environmental benefits are about four times higher than the environmental costs, while for Resources the opposite is true. However, as a single score ratio the nutrient recycling AD scenario also has a positive benefit-cost ratio of 2.13.

4. Conclusions

A two-dimensional approach for measuring the circular economy performance of AD dairy processing effluents was proposed. The results of the work demonstrate the potential to close the material and energy circular economy loops at different levels of the dairy supply chain. The assessment on the AD system level (Level 1), showed significant net positive impact in most of the impact categories (CC, OD, FE, IR, ALO, FD). The analysis at dairy factory level (Level 2) revealed the main "hotspots" of the dairy processing facility, and showed that the AD total GHG emissions can be reduced by about 13%. The values obtained for the MCPI and ECPI circularity indicators reveal the importance of the application of the AD treatment as an instrument of circular economy solutions for dairy effluent treatment. The application of the indicators provides quantitative measure of the material and environmental performance of the energy and nutrient circularity valorisation pathways. The latter can facilitate operational decisions for the implementation of circular economy models aiming at retaining the material value within the system taking into account any possible trade-offs within and between these two domains of CE.

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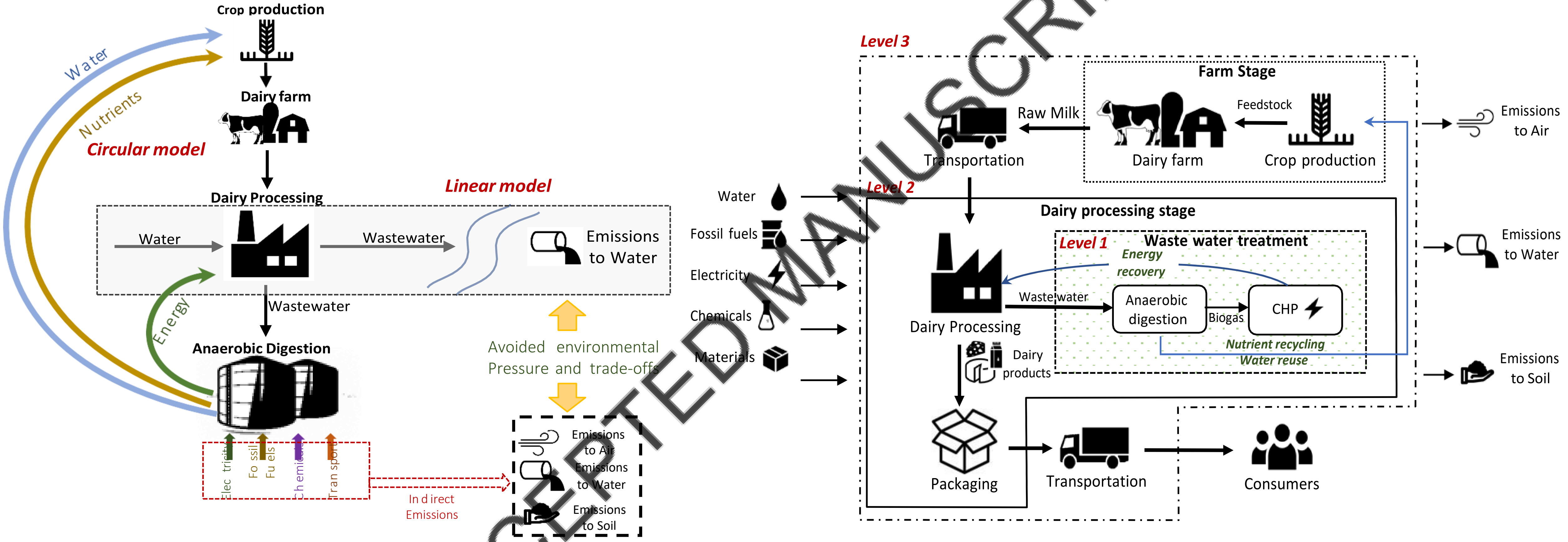
Graphical Abstract



Highlights

- Implementation of circular economy concept in a dairy processing industry
- LCA assessment of the anaerobic treatment of dairy processing effluents
- Material and environmental indicators for measuring circularity performance