MULTILEVEL ENVIRONMENTAL ASSESSMENT OF DAIRY PROCESSING INDUSTRY IN THE CONTEXT OF CIRCULAR ECONOMY

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Abstract

Purpose

This study assesses the environmental impacts and hotspots of the different sub-systems in the dairy supply chain focusing on dairy processing. The analysis of the environmental performance of a UK dairy facility coupled with a full-scale anaerobic digestion unit provides insight on resource, water and energy recovery potential in the dairy sector.

Methods

LCA driven methodology was applied whereas the dairy industry was divided into three subsystems: i) the onsite anaerobic digestion plant, ii) the dairy processing facility and iii) the milk production-related processes.

Results

The anaerobic digestion plant shows environmental benefits for most of the impact categories with 426 MWh/annum excess electricity and 1236 MWh/annum heat produced. In terms of the dairy processing facility, the energy consumption, the packaging materials and the distribution are the main "hotspots", whereas the anaerobic digestion mitigated ~2% of the carbon footprint of the upstream dairy processing. Milk production is the main contributor to the environmental impact of dairy products.

Conclusions

The proposed multilevel assessment provides insight for the environmental performance of innovative technological solutions on a process, system and supply chain level. Considering the complexity of food and especially dairy value chains, the application of multilevel reporting schemes for environmental impact assessment will enable the identification of the priority areas and sustainable goals within each subsystem and provide insight on the effects of critical decisions for all the subsystems.

K**eywords:** Sustainability, dairy supply chain, anaerobic digestion, dairy processing wastewater, LCA,

1. Introduction

Dairy products form an essential source of daily nutrients in human diets [1], whereas the dairy industry, in 2012, accounted for 13.6% of the food and drink industry turnover [2]. However, adaptation and mitigation strategies for reduction of greenhouse gas emissions (GHG) and enhancement of environmental resilience remain main challenge for the dairy industries [3,4]. According to the Environmental Agency [5], a significant amount of wastewater is produced in in the dairy processes whereas water is used at all processing steps, such as cleaning, sanitation, heating, cooling or floor washing. Wastewater is generated by various processing steps (i.e. reverse osmosis for milk concentration) and during cleaning, heating, cooling or floor washing. Several studies discuss the need to reduce the amount of dairy products in European diet patterns [6], which is estimated to be beneficial both the environment [7] and the human health [8].

Several works have assessed the environmental impacts of the dairy sector proposing measures for the improvement of the sustainability of dairy value chains [13], [14]. Dairy farms, have been the focal point of environmental assessments in the dairy sector. Recovery of bioenergy [11] and use of other renewable energy sources [12], recycling of nutrients [13] and wastewater treatment and valorisation [14], have been identified as key factors for the enhancement of the environmental profile of dairy farms. Recently, Kılkış and Kılkış [15], developed a methodological approach for the comparison of different energy and biogas utilization schemes in a dairy farm following circular economy principles. However, a combination of processes is applied for the production of dairy products, including agriculture, livestock farming, manufacturing, packaging, distribution, retail and consumption. Therefore, the development of sustainable dairy value chains requires the reduction of the environmental impacts within each stage of the supply chain. New industrial symbiosis paradigms in Europe have demonstrated efficient management of materials, energy, water and waste flows mainly in industrial applications [16], however applications in the dairy supply chain are still premature. Monitoring of key performance indicators (KPIs) integrating environmental impact and related accountability allocation are main components for the development of an enhanced sustainability framework.

Waste-to-energy systems can facilitate the transition to circular economy [17] and are key solutions for the mitigation of the environmental impacts in the dairy processing sector. Dairy effluents constitute an good feedstock for anaerobic digestion processes since they are characterised by significant organic and microbiological load [18], [18–20]. Thetechno-economic viability of dairy effluents treatment by applying anaerobic digestion has been assessed in various woks [21–25]. At the same time optimization of the operating conditions remains main constrain for the widespread AD implementation in the dairy industry [20] especially without the use of other feedstock.

The main aim of this study is to assess the environmental impacts of the dairy supply chain and the involved stages, to and to identify environmental hotspots at different levels following an LCA approach. The analysis of the system boundaries level, will provide insight on the water, energy, and nutrient recovery potential for closing the circular economy loops. Focus has been put on the treatment of dairy processing effluents. The latter can be seen as a source of valuable resources and energy. In this context the, environmental performance of a UK dairy facility is evaluated including a full-scale high-rate liquid anaerobic digestion unit treating dairy processing effluents.

2. Materials and Methods

2.1. Environmental performance assessment

This session focuses on the application of an LCA driven methodology for impact assessment in the value chain of a dairy industry. LCA is the most widely applied methodology for the analysis of the environmental performance of a system. LCA is a conceptual tool used for the assessment of the environmental impact of a product, process or activity throughout its lifetime. It has the ability to track and trace the transformation of raw material into finished products (i.e. production), distribution of the goods to consumers, usage/consumption, and finally dispose in case of non-perishable product with the potential of the disposed material to be re-used or recycled back into the system. According to the ISO 14040 the main phases of an LCA assessment comprise goal and scope definition, inventory analysis, impact assessment and interpretation of the results which [26]. The key elements of the LCA approach are described in the next sections.

2.1. System description

The chosen site for demonstration of the approach is a dairy processing company located in the South West of United Kingdom. The dairy company produces various fresh and cultured dairy products processing about 42 million litres of milk annually for food manufacturers and service operators in UK, generating approximately 80,000 m^3 wastewater annually. The wastewater is generated from various processing steps, such as milk receiving/storage, pasteurisation, homogenisation, separation/clarification, cheese/butter/milk making, packaging and during cleaning, heating/cooling or floor washing. The dairy wastewater contains milk components, and acid and alkaline detergents used in the equipment cleaning. The wastewater streams generated from the dairy facility are stored in two equalization tanks and fed to an AD reactor. They consist of trade effluent including the spillages and the wash-water rinses and the wastewater generated during soft cheese production (permeate of milk ultrafiltration). The permeate is characterised by high 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. Thus, the influent in the digester is stabilized by the equalization tanks resulting in 21.1 g/L COD and 0.4% Total Suspended Solids (TSS) in the feedstock. The average Organic Loading Rate (OLR) of the anaerobic digestion on COD basis is 3.29 kg $COD/m^3 \cdot d$ while the hydraulic retention time (HRT) is about 6.90 days on average.

2.2. Definition of system boundaries

The selection of system boundaries is one of the most crucial steps in a LCA assessment. According to the LCA standards, the definition of system boundaries is closely related to the goal and scope which results in the selection of different system boundaries depending on the purpose of the study. In dairy sector LCA assessments, the most controversial methodological issue is associated with the setting of a cut-off criteria and consideration of the upstream and downstream processes. The upstream processes include the production of feedstock, breeding cows and milk production (Farm stage) and transportation of milk to dairy processing stage. The downstream processes comprise the packaging and distribution of the products to the customers and the treatment of the generated waste and wastewater (Figure 1). To analyse the effect of the cut-off criteria in the system boundaries definition and to evaluate the environmental impact of the entire dairy supply chain, three different levels of system boundaries have been selected: ***Level 1*** analyses in detail the treatment of dairy effluents; ***Level 2*** is expanded to the physical boundaries of dairy processing factory including packaging and transportation of the generated products. ***Level 3*** covers the entire supply chain of the production of the dairy products – from the feedstock production, cow milk, dairy processing, packaging and distribution to the end consumers.

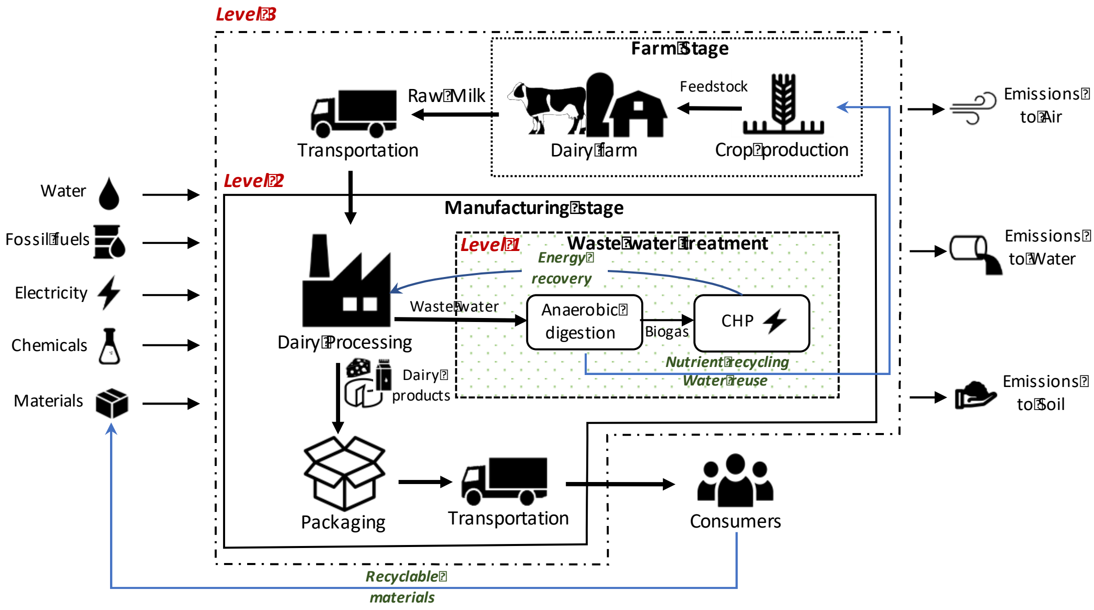

Figure 1 Multilevel system boundaries definition

2.1. Definition of functional unit

In the majority of the existing LCA studies in the dairy sector the functional unit is conventionally based on input or output mass of the products under study or on nutritional and economic aspects of the final dairy products [27]. The aim of the study was to assess the sustainability and the material, water and energy flows of the different sub-systems involved in the dairy value chain and assess their environmental contribution on the dairy processing facility level. Given that the multi-output dairy facility is considered as a "black box" in this study, "1 L of milk processed" was selected as FU. It provides the reference to which all the input and outputs of the system has been calculated.

2.2. Life Cycle Inventory analysis

Data from the dairy processing company were collected for the development of the inventory. Depending on the defined system boundary levels, the life cycle inventory includes input and output flows with a different level of detail. For **Level 1**, comprising the treatment of dairy effluents, detailed primary data for the performance details were collected on process level. Data for one year of operation (2015-16) were used for the operation of the AD plant including feedstock use, water, chemicals and energy consumption, energy generation, transport and digestate management. The input data are based on (i) experimental data and the measurement of main parameters (COD, TSS) (ii) complete mass balance of the process, (iii) literature data for the identification of parameters that are mainly related to emissions characterization and background data.

Figure 1 shows the schematic diagram of 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 average Organic Loading Rate (OLR) of the anaerobic digestion on COD basis is 3.29 kg COD/m^3·d. The hydraulic retention time (HRT) in the anaerobic digester is 6.90 days on average. The operating parameters of the system are summarized in **Table 2**. The produced biogas consists of 64% CH_4 and 36% CO_2 and is led to a combined heat and power (CHP) engine where 2,258 kWh/day electricity on average is generated. The yield is 0.35 m^3 CH_4/kg COD_{rem}. The CHP unit has 105 kW electrical output with 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 fed to the national grid. The AD effluent is characterized by 15.5 g/L COD and 1.3% TSS (average values).

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

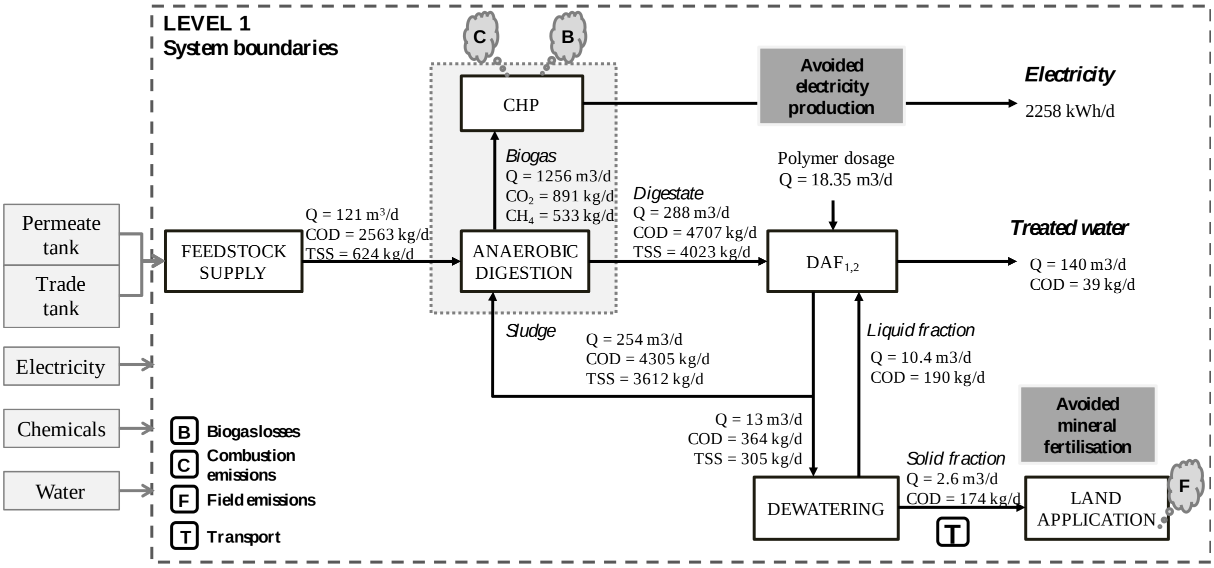

Figure 2. Flowchart of the anaerobic digestion plant treating dairy processing wastewater

Table 1. Summary of input and output parameters.

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. Summary of operating parameters.

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

Since the generated sludge from after the AD is applied in agriculture as a fertilizer, the avoided impacts from the substitution of mineral fertilisers were calculated following the IPCC guidelines [28]. Similarly, it was assumed that electricity produced from biogas combustion can substitute an equivalent amount of electricity from the British electric profile (avoided electricity production).

On **Level 2**, the dairy processing stage has been considered as a "black box" of aggregated processes. Thus, the total input and output energy and material flows for the operation of the entire facility were requested and provided from the dairy company. The transportation for distribution of the products was calculated based on the total load of generated products and the average distance to the retailers.

Finally, background data regarding the environmental impact of the production of raw milk for **Level 3** system boundaries, and for all the upstream environmental impact for the intermediate inputs from the technosphere were obtained by SimaPro software using data from the ecoinvent® databases.

A detailed description of inventory data is given in **Table 3**.

Table 3. Global inventory data of material and energy flows for the whole system per year

Inputs from technosphere	Amount	Unit	Data source
Raw milk	42,000,000	kg/year	Primary data: Dairy factory
Total Water Usage	12450	m3/year	
Chemical Usage			
Dairy processing			
Disinfectant: mainly PAA	51125	kg/year	Primary data: Dairy factory
Detergent	4200	kg/year	
Alkaline detergent: NaOH and KOH	152010	kg/year	
Acid: nitric and phosphoric acid	8470	kg/year	
Enzyme: protease, lipase	11210	kg/year	
Wastewater treatment			
Flocculant (polyvinylvhloride)	27000	kg/year	

Calcium carbonate	1000	kg/year	
Iron (III) chloride, without water,	24000	kg/year	
Sodium Hydroxide	36000	kg/year	
Energy use			
Dairy processing			
Fuel (Kerosene/light oil)	450934	kg/year	
Electricity consumption	3687989	kwh/year	Primary data: Dairy factory
Wastewater treatment			
Electricity consumption	398652	kwh/year	
Packaging materials			
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	Primary data: Dairy factory
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			
Distribution of products	7302050	t-km	
Average Distance to main distribution points	310	km	
Total weifght of generated products	23555	t	
Chemical/ingredients inputs	81725	t-km	
Average distance from providers	360	km	
Packaging materials	251755	t-km	
Average distance from providers	418	km	Primary data: Dairy factory
Raw milk input	840000	t-km	
Average distance from providers	20	km	
Waste disposal	40250	t-km	
Average distance to landfil	50	km	

Outputs to technosphere	Amount	Unit	Data source
Avoided energy production			
AD Electricity Generation from CHP	824039	kwh/year	Primary data: Dairy factory
Avoided fertiliser production			
Generated sludge from anaerobic digestion	805000	kg/year	Primary data: Dairy factory
N fertiliser	283	kg/year	IPCC (2006)
P fertiliser	69	kg/year	Rossier (1998)
Waste			
Wastewater	80346	m3/year	Primary data: Dairy factory
Packaging waste	58.4	t	

2.3. Impact assessment

Most of the LCA studies in dairy sector have been focused on the dairy farm stage [29,30] and only limited works have considered the processing stage [31]. Concerning dairy processing wastewater treatment, there is still a gap in the literature on sound LCA based environmental impact assessment of full scale anaerobic processes. According to the study of Korsström and Lampi [32] the environmental impact of dairy wastewater treatment mainly depends on high organic load of the influent and energy requirements of the applied process. Thus, the application of life cycle impact assessment (LCIA) can facilitate decision making in the dairy industry and increase its sustainability.

The LCA was conducted taking into account the characterisation factors reported by the ReCiPe Midpoint (H) 1.12 method [33] for the following eight impact categories (**Table 4**): 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.

Table 4. List with the selected impact categories

Abbr.	Impact category	Unit
CC	Climate change	kg CO2 eq
OD	Ozone depletion	kg CFC-11 eq
FE	Freshwater eutrophication	kg P eq
IR	Ionising radiation	kBq U235 eq
ALO	Agricultural land occupation	m2a
WD	Water depletion	m3
MD	Metal depletion	kg Fe eq
FD	Fossil depletion	kg oil eq

3. Results and discussion

3.1. LCIA results

3.1.1. Environmental assessment of the AD system (Level 1)

Error! Reference source not found. shows the relative contributions to the impact categories of the subsystems considered in level 1 assessment within the boundaries of the anaerobic digestion system. Environmental credits resulting from the valorization of heat, energy and digestate that is applied as soil conditioner are shown in the figure with negative contributions. The application of the AD process for the treatment of the dairy effluent results in environmental benefits for most of the impact categories. Approximately 48% of the generated electricity is utilized within the anaerobic digestion facility (about 399 MWh/annum), while the surplus electricity (426 MWh/annum) is exported to the national grid. 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). Therefore, 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 62%, 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).

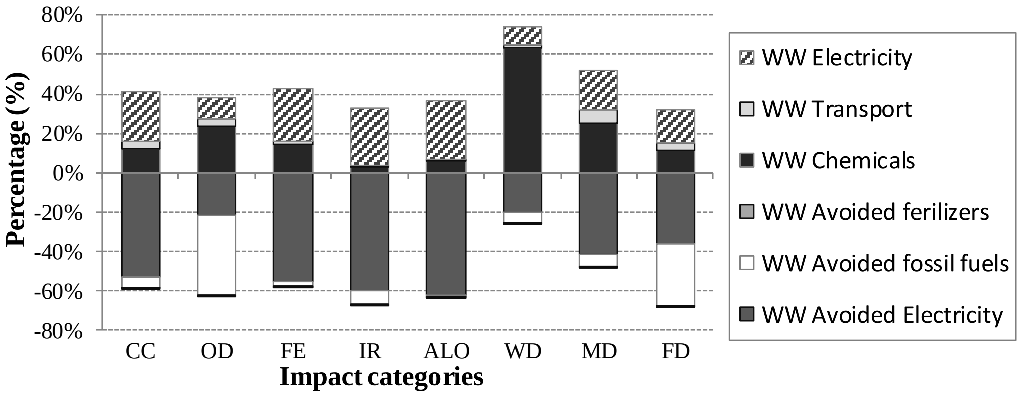

Figure 3: Relative contributions to each impact category from different activities involved in the level 1 assessment.

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 [36], 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. [37] implemented CML 2010 method to determine the environmental impacts of AD installations in UK dairy farms. Mezzullo et al. [38], performed a life cycle assessment of a UK farm with an AD plant that treats dairy cattle waste, using the EI 99 method. Biogas was used solely for the generation of heat displacing the requirements for kerosene fuel.

The results of the current work cannot be directly compared with the cited studies since different methodologies for life cycle assessment are used or different functional units are selected. However, all studies concluded that the AD environmental performance is characterised by increased acidification and eutrophication impacts mainly because of the direct emissions during the operating phase and the open storage and spreading of the digestate. Moreover, Mezzullo et al. [38] concluded that the environmental impacts associated with the construction of the plant had a small contribution compared with the use phase. Additionally, the authors reported that displacement of kerosene of the AD heat production contributes significantly to savings in CO_2 emissions and fossil fuel depletion leading to an overall net negative climate change impact.

3.2. Environmental performance of the dairy processing facility (Level 2)

The expansion of the system boundaries at the dairy facility (level 2) provided insight on the most significant contributors to its environmental profile. The relative contributions to the impact categories of the processing and wastewater treatment, excluding inputs of raw milk, are shown in Error! Reference source not found.. The excess electricity produced from the anaerobic digestion unit, is equal to 170 tn of CO2eq savings in the facility per annum. Benefits are also observed for IR, OD and FD impact categories (relative contribution - benefits equal to 9%, 2% and 4% respectively).

One of the most significant contributors to the majority of the target 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 tn of kerosene are consumed 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 [39]. 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 ~64%) and OD (relative contribution equal to ~27%). Approximately 0.42 kg CO2 eq are emitted per L of milk processed (~15% relative contribution) due to the packaging materials. The environmental impacts of packaging in dairy products have also been identified as an environmental hotspot in other research works [34], [40]. 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 [41].

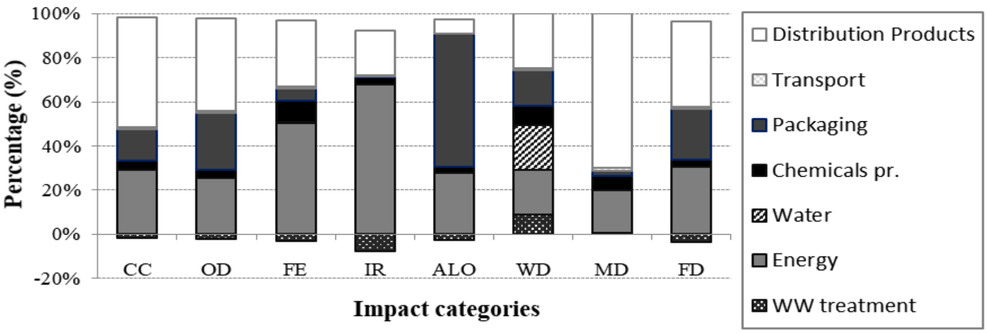

Figure 4: Relative contributions of activities involved at level 2 to each impact category

Significant environmental impacts of the dairy processing plant are attributed to the distribution of the final products. Dairy products' distribution to retailers accounts for 51% of the total carbon footprint of the facility and is attributed to the carbon dioxide (CO2) emitted from the truck's fuel combustion [42] and the long distribution routes. 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 [39], 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.

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

Error! Reference source not found. shows the relative contributions of each sub-system (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%). Palmieri and Salimei [41] 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 [42–44] 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 44%, 40%, 38%, 12% and 11% respectively).

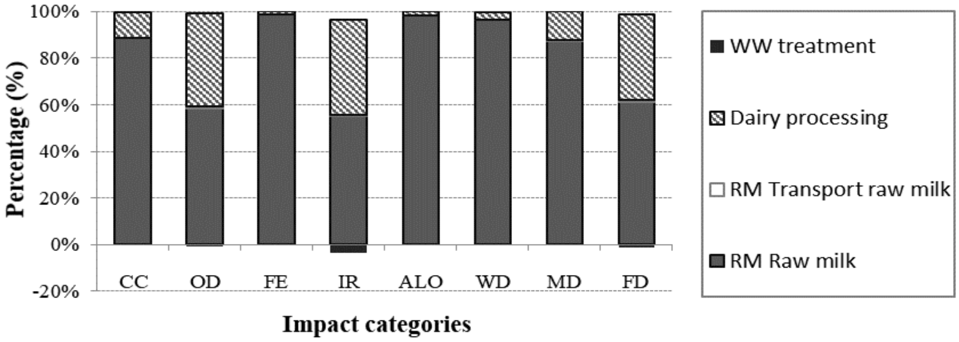

Figure 5 Relative contributions of various activities involved at level 3 to each impact category.

3.3. Effect of system boundaries selection on the LCA analysis

The multilevel environmental assessment applied in this study enables the assessment of practises and techniques applied at all levels and provides insight for the flows and trade-offs between the different sub-systems in the dairy value chain. The main concept is that water, energy and food security cannot be accomplished without an integrated approach addressing the effects of each individual component of the aforementioned subsystems on the other two and without the identification of conflicting or synergistic areas [47]–[49]. For example, the level 1 assessment considering the anaerobic digestion system enabled the technical and environmental evaluation of the wastewater treatment scheme applied in the target dairy facility. The AD plant showed, significant net positive impacts in most of the impact categories. Level 2 reveals the benefits of AD plant in dairy processing facility mitigating about 2% GHG emissions (170 tn/year). In the assessment of the entire dairy supply chain though, the environmental impacts and benefits of an efficient and well-performing AD plant are not more than 0.2% in the majority of the impact categories due to the significantly higher environmental footprint of the dairy farm stage. In this regard, considering the complexity of food and especially dairy value chains, the application of multilevel reporting schemes for environmental impacts assessment will enable the identification of the priority areas and sustainable goals within each subsystem and provide insight on the effects of critical decisions for all the subsystems. Finally, the multilevel environmental analysis will facilitate decision making for the implementation of sustainability measures and integrated management technologies.

4. Conclusions

The current work assesses the environmental performance of a UK dairy supply chain that applies an on-site full-scale anaerobic digestion system for the treatment of dairy processing effluents. The selection of multi-level system boundaries enabled the identification of the environmental priority areas for each sub-system of the value chain and provided insight on the interactions between materials, energy and water flows within the sub-systems. The anaerobic digestion unit assessed at level 1 produces about 426 MWh/annum excess electricity and 1236 MWh/annum heat that is utilized in the facility and exhibits environmental benefits for the majority of the impact categories. The system boundaries were expanded in level 2 assessment in order to integrate the environmental impacts of the upstream dairy facility. The analysis showed that the main “hotspots” of the processing plant are the energy consumption, the packaging materials and the distribution of the final products to the retailers. The AD unit was responsible for ~2% reduction of the carbon footprint of the facility. Level 3 environmental impact assessment of the whole dairy supply chain, identified reduced contribution of the environmental benefits of the AD plant up to 0.2% for the majority of the impact categories. The production of raw milk is the most significant contributor to the environmental impacts of the dairy products. Sustainable dairy supply chains require the application of an integrated approach for mitigation of the environmental impacts within each sub-system. Therefore, the proposed multilevel reporting scheme offers a holistic approach that can provide insight not only for innovative technological solutions technologies that enhance the sustainability on a process, system supply chain level, but also on the water, energy, and nutrient recovery potential of the examined value chains.

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