MOVING TOWARDS THE DEVELOPMENT OF A DAIRY WASTE BIOREFINERY

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ABSTRACT

This study aims to analyse the potential impacts and environmental credits of a high-rate anaerobic digestion (AD) facility treating the industrial effluents of a dairy processing plant following the Life Cycle Assessment (LCA) methodology. Primary data are used from an AD plant treating 44,279 m^3 wastewater annually and operating with 3.29 kg COD/m^3·d Sludge Retention Time (SRT) and 6.9 days Hydraulic Retention Time (HRT) on average. The feedstock has about 15.0 g/L COD and consists of two discrete dairy wastewater streams (i) the trade effluent and (ii) the permeate of cheese ultrafiltration with characteristics similar to cheese whey. The biogas produced (64% CH_4) is fed to a CHP unit generating 393 MWh electricity and exporting 149.34 MWh to the national grid annually.

Environmental results show environmental credits of the AD plant in the majority of the impact categories assessed , mainly because of the avoided impacts due to the electricity generation, which contributes from 41% to 56% to all impact categories. The extended use of chemicals is the most significant *hotspot* to Ozone Depletion and Photochemical oxidant formation with 27% and 22% contribution respectively, whereas diffuse emissions from biogas losses and digestate land application emit about 68.9 tn CO_{2eq} annually. Upgrading the Dissolved Air Flotation (DAF) units used for thickening and using the heat generated in the CHP unit can further improve the environmental profile of the AD plant increasing the net negative GHGs emissions from -0.09 to -2.40 kg CO_{2eq}/m^3 feedstock.

Keywords: waste treatment; dairy industry; sustainable production; anaerobic digestion; Life Cycle Assessment (LCA).

1. Introduction

Dairy products form an essential element of the world's food consumption patterns mainly due to their economic and nutritional importance [1]. The dairy industry is one of the largest sub-sectors of the food industry in Europe [2]. Specifically, UK is placed third in terms of milk production in Europe and tenth largest in the world [3] with milk production worth £4.6 bn in 2014 [4]. However, according to the Environmental Agency [5], a huge amount of wastewater is produced in the dairy processing industry mainly due to disinfection and health and safety requirements. Wastewater is generated by various processing steps (i.e. reverse osmosis for milk concentration) and during cleaning, heating, cooling or floor washing. The European Comission Directorate [6] has reported variable volume for wastewater generation from the milk, milk powder and cheese dairy processing. The latter depends on the production processes applied, the materials used in the production line and the end products; the amount varies from 0.4-60 l/kg of processed milk. Additionally, the dairy wastewater streams are characterised by significant organic and microbiological load [7]. Typically, the COD (Chemical Oxygen Demand) of dairy wastewater ranges from 0.1-100 kg/m^3, mainly due to milk carbohydrates and proteins, whereas the presence of fats (0.07-2.9 kg/m^3), nutrients (nitrogen and phosphorous) and suspended solids (0.2-5.1 kg/m^3) increases the contamination levels [7]. The variable composition of dairy effluents affects its biodegradability [8].

Biological treatment technologies, for instance trickling filters, activated sludge process and anaerobic treatment processes have been extensively used for the treatment of dairy processing wastewater [9-11]. Attention has been focused, though, mainly in anaerobic processes, due to the absence of aeration, small sludge production and low footprint [11, 12]. Consequently, dairy effluents have already been considered as an attractive feedstock for anaerobic digestion processes [7, 13, 14].

Thus, several studies have evaluated the techno-economic viability of dairy effluents treatment by applying anaerobic digestion [11, 14-18]. Different configurations have been used, including

Upflow Anaerobic Sludge Blanket (UASB), Continuously Stirred Tank (CST) reactors and anaerobic filters [19, 20]. However, the instability of these processes together with the slow reaction rates have led to a limited number of full-scale applications [21]. Thus, the optimization of the operating conditions has been found to be the main constrain for the widespread AD \implementation in the dairy industry [14].

Innovative technologies involving co-digestion of dairy feedstock (mainly cheese whey) with livestock manure have been also tested at pilot scale with better results for variable dairy effluents [16, 17, 22-24]. Co-digestion of these waste streams is advantageous, since it results in higher CH_4 rates will acidification problems can be partially neutralized [16, 17, 23]. However, feeding rates of the substrates can significantly affect the stability of the process [16, 17, 23].

Concerning the environmental impact of AD processes, there is still uncertainty from a life-cycle perspective. The latter is directly affected by the feedstock used [25]. To the best of our knowledge, a sustainability study on the anaerobic treatment in dairy processing wastewater streams is missing from the literature from an environmental perspective. Life Cycle Assessment (LCA) can be used as decision making tool; it has been used for the environmental impact assessment of various food waste management schemes that include anaerobic digestion [26-28]. The current work analyses the environmental performance of the high-rate liquid anaerobic digestion process associated for the treatment of effluents originating from a dairy industry in the UK.

2. Materials and Methods

LCA methodology in accordance with the principles and guidelines established by ISO standards [29, 30] was applied in the current work.

2.1. Goal and scope definition

The main goal of the study was to evaluate from a cradle-to-grave perspective the environmental burdens related to the anaerobic digestion process implemented for the management of wastewater from a dairy company located in the South West of United Kingdom. The most 'critical' stages (*hotspots*) from an environmental perspective were identified and potential improvement scenarios were proposed and evaluated to attain environmental benefits.

2.2. Functional unit

According to ISO standards, the functional unit (FU) is defined as the main function of the system expressed in quantitative terms [29]. The aim of the study was to assess the sustainability of the AD plant towards treating dairy processing wastewater, thus '1 m^3 of Dairy Wastewater Feedstock (DWF)' was selected as FU. It provides the reference to which all the input and outputs of the system will be calculated.

2.3. System description

The dairy company produces various fresh and cultured dairy products processing about 35 million litres of milk annually for food manufacturers and service operators in UK, generating approximately 44,279 m^3 wastewater annually. **Fig. 1** shows the supply chain and the system boundaries of the anaerobic digestion plant considered in the analysis. The system includes (i) the production and transport of all input materials (chemicals, water, and electricity), (ii) the electricity production in the CHP unit (iii) the direct GHGs emissions of the AD plant and (iv) the management of the digestate.

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. Two discrete wastewater streams are generated in the dairy facility and fed to the AD reactor through two equalization tanks; (i) the trade effluent including the spillages and the wash-water rinses and (ii) 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 characteristics of the feedstock and the treated effluent are shown in **Table 1.**

The average Organic Loading Rate (OLR) of the anaerobic digestion on COD basis for the baseline scenario is 3.29 kg COD/$m^3 \cdot d$. 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 1722 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. **Fig. 1** shows the complete mass balance of the system considered in the baseline scenario.

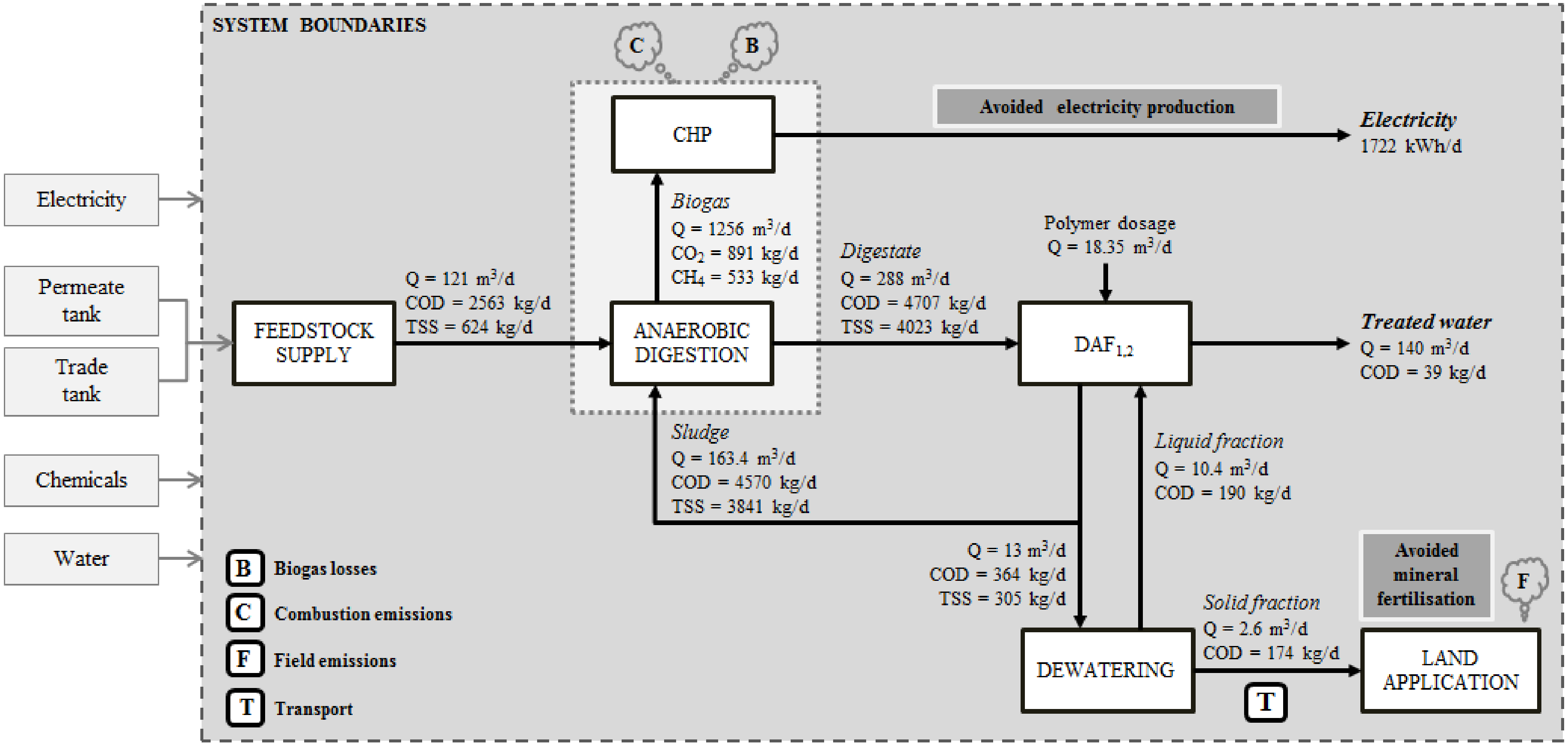

Fig. 1. Flowchart and system boundaries.

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

2.4. Life Cycle Inventory analysis

Real data from a full scale anaerobic digestion system, processing dairy wastewater effluents are used in the analysis for the development of the inventory. Primary data for one year of operation (2015-16) were used for the whole supply chain of the AD plant including feedstock use, water, chemicals and energy consumption, energy generation, transport and digestate management. The development of the inventory is 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.

Given that the wastewater generated in the dairy plant is fed to the AD reactor the transport distance was eliminated from the study. The average transport distance to the digestate management facility is about 15 km. 1.5% of the biogas generated is assumed to be released to the atmosphere from the anaerobic digester and the CHP unit based on the study [31]. Moreover, combustion emissions derived from CHP unit were calculated according to NERI [32]. However, since biogas production has its origin in biological matter, both CO_2 and CH_4 emitted from biogas combustion were accounted as biogenic emissions [33-35]. This is in accordance with DETR [36], where main guidelines for GHG reporting by organizations/companies in the UK are proposed. Field emissions due to the application of the different organic sources from digestate management were included in the analysis. Direct (N_2O) and indirect (NO_x, NO_3, NO_3^-) nitrogen emissions were estimated based on the Tier 1 method proposed by the International Panel on Climate Change [37], whereas phosphate (PO_4^{-3}) emissions to water were calculated using with a conversion factor of 0.01 kg PO_4^{-3}-P·kg^{-1} of applied P [38].

Avoided impacts from the substitution of mineral fertilisers were also calculated, following the IPCC guidelines [37]. The amount of nitrogen and phosphorous based mineral fertilisers that can be replaced by organic sources was estimated according to Birkmose [39]. 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). Thus, a system expansion strategy was considered in this study, avoiding allocation procedures regarding digestate management and electricity generation.

Finally, background data regarding the production of all inputs required in the system were taken from the ecoinvent® database [40-43]. The British electricity mix was used in terms of electricity consumption.

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

Table 3. Global inventory data per functional unit (1 m^3 of DWF) for the whole system.

Inputs from technosphere	Amount	Unit	Data sources
Materials			
Raw materials			
Permeate	0.8	m^3	
Trade	0.2	m^3	Primary data: Dairy factory
Water	0.15	m^3	
Chemicals			
Sodium hydroxide	0.24	kg	
Ferric chloride	0.27	kg	Primary data: Dairy factory
Sodium carbonate	0.04	kg	Secondary data: Althaus et al. (2007)
Polymer	0.61	kg	
Energy use			
Electricity	8.87	kWh	Secondary data: Dones et al. (2007)
Transport			
Truck	15.0	km	Secondary data: Spielmann et al. (2007)
Outputs to technosphere	**Amount**	**Unit**	**Data sources**
Avoided fertiliser production			
N fertiliser	5.44	g	IPCC (2006)
P fertiliser	1.33	g	Rossier (1998)
Avoided energy production			
Electricity	14.2	kWh	Primary data: Dairy factory
Outputs to environment	**Amount**	**Unit**	**Data sources**
Air emissions			
Methane	0.06	kg	De Vries et al. (2012)
Carbon dioxide	11.0	kg	De Vries et al. (2012)
Nitrogen oxides	0.03	kg	De Vries et al. (2012)
Carbon monoxide	0.04	kg	De Vries et al. (2012)
NMVOC	1.32	g	De Vries et al. (2012)
Sulphur dioxide	2.47	g	De Vries et al. (2012)
Dinitrogen monoxide	0.11	g	IPCC (2006)
Ammonia	1.76	g	IPCC (2006)
Water emissions			
Nitrate	9.64	g	IPCC (2006)
Phosphate	0.042	g	Rossier (1998)
Avoided fertiliser application			
Dinitrogen monoxide	0.09	g	IPCC (2006)
Ammonia	0.58	g	IPCC (2006)
Nitrate	7.23	g	IPCC (2006)
Phosphate	0.041	g	Rossier (1998)

2.5. Impact assessment

The LCA was conducted taken into account the characterisation factors reported by the ReCiPe Midpoint (H) 1.12 method [44] for the following eight impact categories (**Table 4**): climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication

(FE), marine eutrophication (ME), photochemical oxidant formation (POF) and fossil depletion (FD). The software SimaPro v8.0.5.13 was used for the computational implementation of the inventories [45].

Table 4. Characterisation results per functional unit (1 m^3 of DWF) relative to the whole process.

Impact categories	**Units**	**Characterisation results**
Climate change (CC)	kg CO_2 eq	-0.09
Ozone depletion (OD)	g CFC-11 eq	$1.43 \cdot 10^{-4}$
Terrestrial acidification (TA)	g SO_2 eq	13.1
Freshwater eutrophication (FE)	g P eq	-0.62
Marine eutrophication (ME)	g N eq	-55.8
Photochemical oxidant formation (POF)	g NMVOC	0.90
Fossil depletion (FD)	kg oil eq	-0.17

3. Results and Discussion

3.1. Environmental performance of AD treating dairy effluents

The results for the impact categories assessed normalized to the functional unit (1 m^3 DWF) are shown in **Table 4**. Positive values are indicative of environmental impacts whereas negative values display environmental credits from avoided processes due to valorisation of the produced biogas and digestate application as soil conditioner. The environmental profile of the AD plant is generally positive for most of the examined impact categories (CC, FE, ME, FD) showing environmental benefits.

Fig. 2 shows the contributing factors for the selected impact categories. The electricity produced from the biogas combustion (avoided electricity production) is mainly responsible for the environmental benefits of the AD process with overall contribution ranging from 41.8% to 59.4%, for all impact categories. Approximately 62.5% of the generated electricity is consumed within the facility (about 393 MWh/annum) whereas the surplus electricity (235 MWh/annum) is exported to the national grid. Thus, 0.09 kg CO_{2eq} per m^3 of dairy wastewater (760 tn on average of CO_{2eq}) are saved annually, due to the electricity surplus.

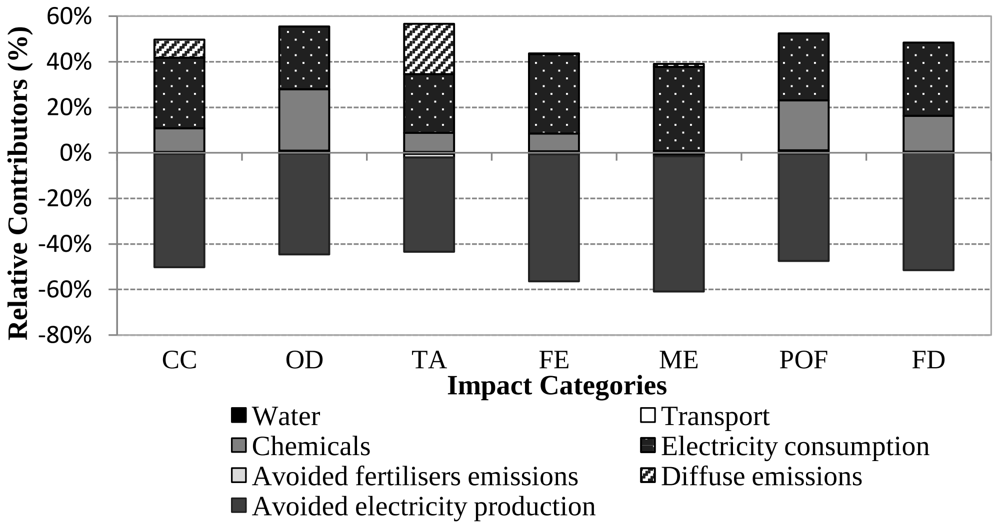

Fig. 2. Relative contributions to each impact category from different activities involved in the system. Climate change: CC, ozone depletion: OD, terrestrial acidification: TA, freshwater eutrophication: FE, marine eutrophication: ME, photochemical oxidant formation: POF and fossil depletion: FD.

On the contrary, the chemicals used in the AD plant are mainly responsible for the negative environmental impacts in the majority of the impact categories and particularly for the OD and POF (26.9 and 22% respectively). Diffuse emissions (biogas losses and fertilisers application) are also significant contributors to CC and TA, with 7.9% (68.9 tn CO_{2eq} annually) and 22.5% (0.96 tn SO_{2eq} annually) contribution, respectively.

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 [25] 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. [46] implemented CML 2010 method to determine the environmental impacts of AD installations in UK dairy farms.

Moreover, bioenergy options for dairy farms were also assessed based on environmental and economic modelling. Mezzullo et al. [47] 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. [47] 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. Sensitivity analysis

The analysis showed that chemicals consumption is the main 'hotspot' in the AD plant. Additionally, the environmental profile of the AD plant can be further improved through the valorisation of the heat generated in the CHP unit, especially since the dairy plant has already installed the technology to use this stream in the dairy processing plant. Consequently, the sensitivity analysis aims to assess the impacts of (i) reducing the chemicals in the AD and (ii) using the heat produced, in the environmental profile of the facility.

3.2.1. Scenario 1; Chemicals use

The polymer dosage in the DAF unit is high (about 240 mg/l) contributing significantly to the operating costs of the wastewater treatment of the dairy effluent as well as to the environmental profile of the plant. Chemical-related impacts are affected by the high polymer dosage from 12% to 86% for all impact categories.

However, several studies in the literature have reported the use of different polymer dosage for thickening of digestate sludge. Ross et al. [48] applied an industrial DAF unit for pre-treatment of industrial waste with a cationic polymer dosage of 15-20 mg/l; the authors demonstrated the importance of DAF design and the advances of chemical flocculants. The USA national manual of good practice for biosolids [49] states 1.36-4.5 kg preferable addition of polymer per dry ton for gravity belt thickeners and 1.81-4.5 kg per dry ton for DAF thickeners. Finally, Ross and Valentine [50] reported a typical dosage of 2-14 mg/L in a biological/dissolved air flotation process for the treatment of food and dairy processing wastewater. On the other hand, Fogarty and Fosshage [51] proposed the upgrading the hydraulic separation zone, the sludge removal mechanism and the air dissolving system of existing rectangular DAF technologies in order to reduce the polymer dosage up to 35%; the latter improved the TSS removal up to 50% and increased the DAF capacity up to 15%.

The influent and effluent characteristics of the aforementioned studies are given in **Table 5**. The thickening process exhibits high removal efficiencies for biological treatment effluents with polymer dosage ranging from 2-20 mg/l. Thus, in Scenario 1 the upgrading the DAF unit is examined in order to achieve the same removal efficiencies while dosing lower amounts of polymers. The dosage used is 5.56 kg/day of polymer that results in 20 mg/L polymer concentration in the thickening unit.

The results in **Fig. 3** indicate that optimising the DAF unit and reducing the polymer dosage can reduce the environmental impacts of the AD plant. The net negative emissions in Scenario 2 are -1.29 kg CO_{2eq} per m^3 of feedstock equivalent to -57.3 tn CO_{2eq} per year. Additionally, reductions in TA, POF and FD impact categories occur (26% and 19% and 20% respectively).

Table 5. Industrial wastewater full scale thickening technologies, removal efficiency (CDAF: Conventional DAF, UDAF: Upgraded DAF)

	Ross et al. (2008)						Fogarty and Fosshage (2001)		Ross et al. (2000)	
	Activated sludge system coupled with DAF clarification and flucculation tank for dairy processor		High rate anaerobic effluent treatment using a DAF clarifier with flocculation tank for a beverage plant		Activated sludge coupled with DAF clarification and flucculation tank for a snack food plant		Dissolved Air Upgrade for a DAF system in the Pulp and Paper industry		Pretreatment of industrial poultry wastewater	
Parameter	**DAF Influent**	**% Removal**	**DAF Influent**	**% Removal**	**DAF Influent**	**% Removal**	**CDAF effluent**	**UDAF (%)**	**DAF influent**	**% Removal**
Flow, m^3/h	10.7	-	45	-	189	-	454	+66.7%	75	-
BOD, mg/L	-	99%	-	-	-	-	-	-	-	-
TSS, mg/L	4000	99%	716	82%	4479	99	170	120	43,706	99%
TS,mg/L	-	-	92	84%	-	-	-	-	-	-
COD, mg/L	-	-	1110	67%	-	96	-	-	63,446	91.7%
Polymer addition, mg/l	2-15 (4)		2-15 (4)		2-15 (4)		-	-35%	15-20	

3.2.2. Scenario 2; heat valorisation

Electricity and heat are co-produced from biogas combustion in the CHP unit. In the baseline scenario the produced electricity was directly injected into the grid, whereas heat was considered to be released to the atmosphere. In this context, an alternative scenario involving heat valorisation is proposed. Thus, assuming 50% efficiency of the CHP unit, 2,690 kWh of heat is generated and can be used in the facility at daily basis resulting in environmental credits due to the avoided heat production from other non-renewable sources. Given that in the dairy processing facility a kerosene boiler is used for heating purposes, the CHP heat exploitation is considered to replace equivalent heat produced from the boiler, thus kerosene. Accordingly, energy allocation is assumed between electricity and heat produced in the system. Consequently, 1 kWh of energy produced in CHP unit is equivalent to 0.64 kWh of heat and 0.36 kWh of electricity.

The comparison between the Base Scenario and Scenario 2 is shown in **Fig. 3**. A moderate reduction in FE and POF (13% and 19% respectively) is observed whereas the ajority of the impact categories show significant reductions ranging up to 74%, with OD ecoming negative (from 1.43×10^{-4} to -1.07×10^{-3} g CFC-11_{eq}/m^3 of feedstock). Thus, the use of the CHP heat upstream in the dairy processing can significantly improve the environmental profile of the AD plant.

3.2.3. Scenario 3; Scenario 1 and 2 combination

Finally, a global sensitivity analysis was performed taking into account all the aforementioned considerations in order to evaluate their global influence over the whole system (**Fig. 3**). The two developed scenarios (Scenario 1 and 2) result in enhanced environmental performance of the AD plant. Specifically, impacts related with TA are decreased by 94% (from 13.12 to 0.77 g SO_2eq/ m^3 of feedstock) and the POF is also decreased by 38% (from 32.61 to 20.07 kg NMVOC/ m^3 of feedstock). Additionally, 96.1% reduction is observed for the total GHGs emissions of the AD plant (from -0.09 to -2.4 kg CO_{2eq}/ m^3 of feedstock). Consequently, upgrading the DAF unit and valorising the heat generated in the CHP unit can significantly improve the environmental profile of the AD plant.

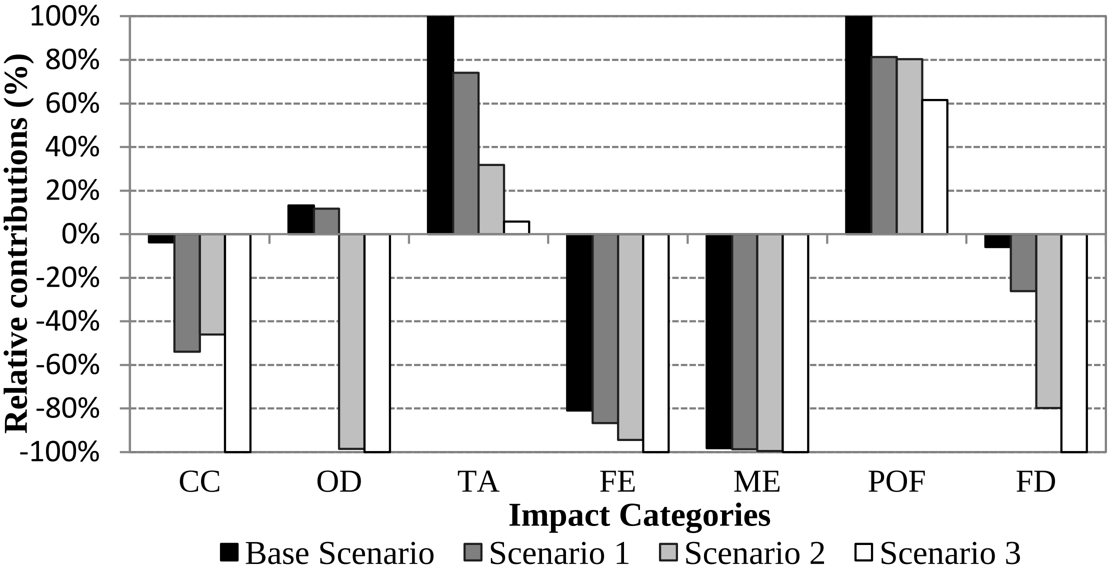

Fig. 3. Comparative global environmental results between Base Scenario and alternative scenarios proposed for assessment: Scenario 1, Scenario 2, Scenario 3. Climate change: CC, ozone depletion: OD, terrestrial acidification: TA, freshwater eutrophication: FE, marine eutrophication: ME, photochemical oxidant formation: POF and fossil depletion: FD.

Conclusions

The current work assesses the sustainability of a high-rate AD facility located in the UK processing dairy wastewater. The plant achieves 90% COD removal efficiency and 64% methane concentration in the biogas. The generation of 1 kWh of energy in the CHP unit has -0.09 kg CO_{2eq} negative emissions mainly because of the offsetting of the environmental impacts due to the electricity production. Similarly, the assessment showed environmental benefits for FE, ME and FD impact categories. This work demonstrated that the plant's environmental profile can be further improved through the upgrading of the DAF unit and the valorisation of the heat generated at CHP unit. Future work can be focused on the effect of the AD plant in the environmental performance of the upstream dairy processing facility.

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