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Environmental impacts of milk powder and butter manufactured in the Republic of Ireland

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Abstract

The abolition of the milk quota system that was in place in Europe was abolished in 2015, which instigated an immediate increase in milk production in many European countries. This increase will aid in addressing the world's ever growing demand for food, but will incur increased stresses on the environmental impact and sustainability of the dairy industry. In this study, an environmental life cycle assessment was performed in order to estimate the environmental impacts associated with the manufacture of milk powder and butter in the Republic of Ireland. A farm gate to processing factory gate analysis, which includes raw milk transportation, processing into each product and packaging, is assessed in this study. Operational data was obtained from 5 dairy processing factories that produce milk powder (4 of which also produce butter).

Results of each environmental impact category are presented per kilogram of product. Energy consumption (raw milk transportation and on-site electrical and thermal energy usage) contributes, on average, 89% and 78% of the total global warming potential, for milk powder and butter respectively, for the life cycle stages assessed. Similarly, energy consumption contributes, on average, 86% and 96% of the total terrestrial acidification potential for milk powder and butter respectively, for these life cycle stages. Emissions associated with wastewater treatment contribute approximately 10% and 40% to the total freshwater eutrophication potential and marine eutrophication potential, respectively, for both milk powder and butter production. In addition, packaging materials also has a significant contribution to these environmental impact categories for butter production.

Results were also presented for three milk powder products being manufactured by the factories surveyed: skim milk powder, whole milk powder and full fat milk powder. The analysis presented in this paper helps to identify opportunities to reduce the environmental impacts associated with post-farm processing of milk powder and butter.

Keywords: butter; dairy; Ireland; life cycle assessment; milk powder; milk processing.

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1 Introduction

Global milk production is estimated at approximately 735 billion litres, where the largest producer is the European Union (EU) at 156 billion litres (Fonterra, 2014). Furthermore, according to a European Commission report (EC, 2015), the annual growth rate of the global dairy industry is predicted to be 2.4% per annum, which is approximately 1.4 million tonnes of dairy products, over the next 10 years. If the EU is to meet its climate and energy targets for 2020 of a 20% increase in energy efficiency and a 20% reduction in greenhouse gas (GHG) emissions (EU, 2008), the dairy industry must strive to reduce impacts and increase sustainability to deal with this expected increase in milk production.

Currently, the Republic of Ireland is on the brink of a new era for the dairy industry. In March 2015, the quotas, which restricted milk production since 1984, were abolished. As a result, milk production is expected to increase by 50% by 2020, based on the reference years 2007 to 2009 (Farrelly et al., 2014), with a yearly increase of approximately 35% observed since March 2015 compared to the reference years (Figure 1). This brought the total milk produced on dairy farms in the Republic of Ireland in 2015 to a record high of 6.4 billion litres (CSO, 2016). This increase in the volume of milk produced and processed, together with stringent measures on emissions from the industry is driving the need for innovative technological and operational solutions within the dairy processing industry.

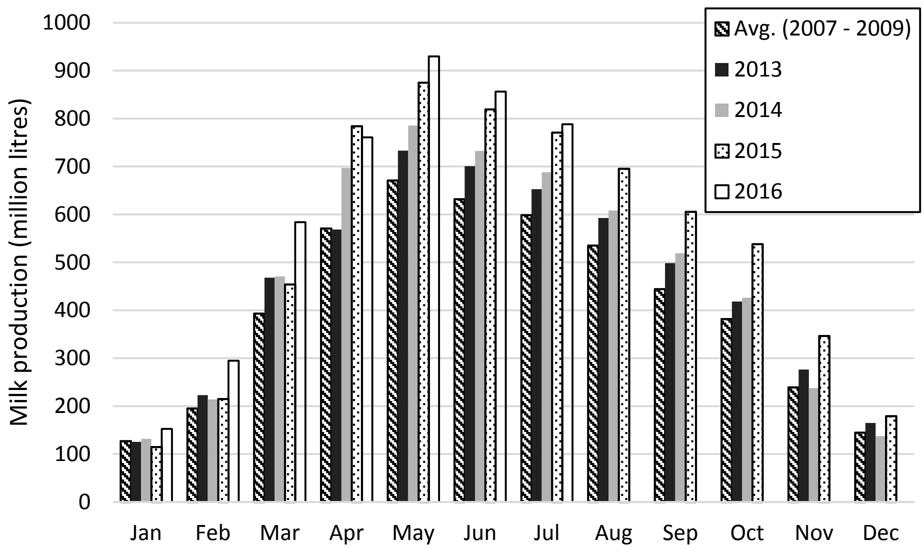

Figure 1: Monthly milk production in the Republic of Ireland (Source data: CSO (2016))

When evaluating the sustainability of an industry, three aspects must be included, which are environmental, social and economic impacts. Life cycle assessment (LCA) is a useful tool for estimating the environmental impacts of the manufacture of dairy products. In addition, the main contributors

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to these emissions are highlighted within the analysis and its interpretation (for example, specific energy or resource consumption).

LCA has been used in studies of many major manufacturing countries of dairy products in order to evaluate the environmental and socio-economic impacts of the industry and its products as summarised by (Finnegan et al., 2015). However, a limited number of these studies consider the environmental impact of milk powder (Finnegan et al., 2015; Flysjö, 2012; Flysjö et al., 2014; Vergé et al., 2013) and butter (Djekic et al., 2014; Doublet et al., 2013; Finnegan et al., 2015; Flysjö, 2012; Flysjö et al., 2014; Nilsson et al., 2010; Sheane et al., 2011; Vergé et al., 2013) manufacture. In many of these studies, milk powder and butter have been included in an analysis of various dairy products. However, Nilsson et al. (2010) performed a comparative LCA of margarine and butter consumed in the UK, Germany and France. A cradle to factory gate boundary condition was used and a number of environmental impacts, including global warming potential, acidification potential and eutrophication potential, were estimated. Previously, Finnegan et al. (2015) estimated the global warming potential associated with the production of dairy products in the Republic of Ireland using country-level data. The analysis performed in this paper will build on this study by increasing accuracy, by using site specific data and including additional processes within the manufacture stage, as well as exploring additional environmental impacts of a number of post-farm dairy product life cycle stages. In order to determine the variability of the data used in an LCA and its effect on the results, an uncertainty analysis is used. A number of previous studies, including Aguirre-Villegas et al. (2012), Kim et al. (2013) and Broekema and Kramer (2014), employed Monte Carlo simulation to perform an uncertainty analysis.

The purpose of this study is to examine environmental impact associated with manufacture of milk powder, which includes skim milk powder, whole milk powder and full fat milk powder, and butter in the Republic of Ireland using LCA. The results of this study are compared to similar European studies in order to benchmark Ireland's environmental performance for the manufacture of milk powder and butter. The results of this study identifies the major contributors to the various impact categories. This information will be instrumental in identifying opportunities for reducing the environmental impact of the industry.

2 Materials and methods

This study has been structured in accordance with the LCA guidelines of the International Organisation for Standardisation (ISO): ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). Furthermore, particular attention was paid to the LCA methodology for the dairy industry published by the International Dairy Federation (FIL-IDF, 2015). The FIL-IDF LCA methodology encompasses a number of existing standards and guidelines, including ISO 14040 (ISO, 2006a), ISO 14044 (ISO, 2006b), PAS2050 (BSI, 2011) and the Intergovernmental Panel on Climate Change (IPCC, 2007). The LCI data sets used in this study are based on site specific data, national data and the ecoinvent database Version 3 (Weidema et al., 2013), which is discussed further in Section 2.2. Both direct (on-site) and indirect (off-site) environmental impacts are included in the analysis using emission factors based on the ecoinvent database Version 3 (Weidema et al., 2013), which is discussed in greater detail in Section 3.1. The results of the analysis are compared to international studies in order to benchmark the environmental performance of the industry in Ireland, which is presented in Section 3.3.

2.1 Goal, scope and system boundaries of the study

The primary goal of this study is to perform an environmental LCA of milk powder and butter manufactured in the Republic of Ireland from farm gate to dairy processing factory gate. This assessment is performed in order to estimate the environmental impacts associated with butter and milk powder. The life cycle stages included within the system boundary of the study are raw milk transportation to the processing factory, processing of raw milk into each product and packaging of the final product. These processes are summarised graphically in Figure 2. The functional units in this study are defined as 1 kilogram (kg) of packaged milk powder and 1 kg of packaged butter, as advised by FIL-IDF (2015). It is important to note that the environmental impacts associated with raw milk production, along with other inputted ingredients, is not included in the current study.

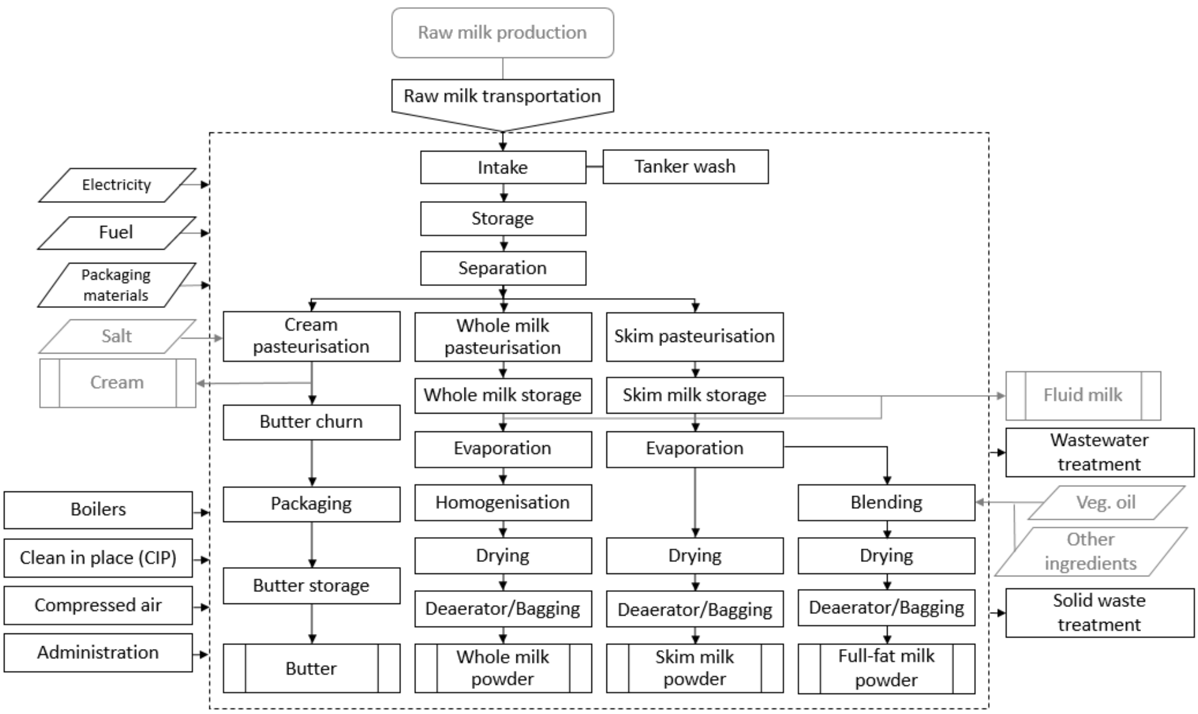

Figure 2: Processes involved in the manufacture of milk powder and butter (Elements in grey have been omitted from the analysis; Dashed line: boundary of dairy processing factory; Solid line: interaction between processes/inputs/outputs; Rectangular elements: system process; Parallelogram elements: energy and resource input; Modified rectangular elements: Outputted dairy product)

2.2 Life cycle inventory analysis

The life cycle inventory (LCI) was generated by surveying a number of dairy processing factories within the Republic of Ireland which produce one or both products. Operational data (for years circa 2013) was obtained from 5 dairy processing factories that produce milk powder, where 4 of the factories also produce butter and, in some cases, other minor by-products. These factories processed approximately 24% of the total raw milk processed in the Republic of Ireland in 2013, which was 5.83 billion litres (CSO, 2016). The total milk powder manufactured by these factories was approximately 142 kilo-tonnes (kT). Skim milk powder makes up approximately 33 kT of the total for milk powder, which represents approximately 67% of the total skim milk powder produced in the Republic of Ireland in 2013 of 49.5 kT (CSO, 2016). In addition, the total butter manufactured by these factories was approximately 53 kT, which represents approximately 35% of the total butter produced in the Republic of Ireland in 2013 (CSO, 2016).

The data requested from industry, which was constructed in accordance to FIL-IDF (2015), was: the volume raw milk processed and other ingredients; raw milk transportation details; production statistics of the dairy processing factory; electrical and thermal energy consumption and breakdown between processes; water consumption and breakdown between processes; chemical usage, particular for cleaning; packaging details and raw materials used; on-site wastewater treatment details; and quantity of solid waste generated and amount recycled. Where aspects of the survey are not monitored on-site, engineering estimates or national averages were used. A summary of the LCI for the manufacture of 1 kg of milk powder and 1 kg of butter in the Republic of Ireland in 2013 is presented in Table 1.

Table 1: Summary LCI for the manufacture of 1 kg of milk powder and 1 kg of butter in Ireland (range, mean and standard deviation (SD) of annual values per kg product obtained for each factory in 2013)

		Milk powder			Butter		
	Unit	**Range**	**Mean (SD)**	**n**	**Range**	**Mean (SD)**	**n**
Inputs:							
Raw milk	*L*	5.12 - 9.22	7.34 (1.54)	5	4.53 - 8.12	6.05 (1.76)	4
Raw milk transportation	*kg.km*	682 - 1608	1191 (424)	4	479 - 1416	1102 (429)	3

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Energy input:							
Electrical energy [a]	*kWh*	0.27 - 0.56	0.4 (0.13)	5	0.2 - 0.62	0.35 (0.19)	4
Thermal energy [a]	*kWh*	1.96 - 5.44	3.39 (1.61)	5	0.14 - 0.82	0.36 (0.31)	4
Chemical usage:							
Sodium hydroxide	*g*	6.6 - 18.7	14.4 (4.6)	3	1.5 - 16.5	8.4 (8)	2
Nitric acid	*g*	2.9 - 6.2	4.5 (1.3)	3	0.5 - 5.5	3 (2.4)	2
Water	*L*	3.6 - 17.9	10.2 (6.7)	5	2.4 - 7.2	5 (2.4)	4
Primary packaging	*g*	13.6 - 14	13.9 (0.2)	3	14 - 30	25.9 (7.9)	2
Outputs:							
Wastewater treated [b]	*L*	1.7 - 24.1	11.4 (8.1)	5	3.5 - 9.9	7.8 (3)	4
Solid waste	*g*	3.2 - 118	50.4 (41.8)	5	2.7 - 39.7	27.2 (16.6)	4

[a] Breakdown of usage given in Table 2

[b] Reported on-site wastewater treatment details are given in Table 3

2.2.1 Raw milk

The volumes of raw milk reported for the production of one kg of milk powder and one kg of butter are presented in Table 1. The transportation of the Raw milk from the dairy farm to the dairy processing factory has been included within the study. Either the average distance per raw milk collection route or the total diesel used by the factory relating to raw milk transportation was specified within the survey. Where total diesel used was specified, it was converted to a distance, which was assumed to be 2.84 km/litre diesel for a 50% laden milk lorry, in order to calculate the average distance per raw milk collection route. Of the Irish dairy processing factories surveyed in the project that reported a value for raw milk transportation (4 of the dairy processing factories used in this study and 2 other dairy processing factories in Ireland), the average distance per raw milk collection route was found to be 169 km. This is the value that was used where a factory did not specify details for raw milk transportation. This value is much greater than the value specified by Quinlan (2013) of 79 km per return trip per route. It is also worth noting that the distance of 169 km is far less than that found by Ulrich et al. (2013) for the US dairy industry, where the average round trip distance was 850 km.

2.2.2 On-site energy usage

The reported breakdown of electrical and thermal energy usage between processes or equipment is presented in Table 2. The major consumers of energy are associated with the direct processing of the products. A graphical breakdown in the form of pie charts are also displayed in Figure 3 and Figure 4 for milk powder and butter manufacture, respectively. In milk powder manufacture, the largest consumer of electrical energy is the dryer (24%) and the largest consumers of thermal energy are the dryer (52%) and the evaporator (39%). In butter manufacture, the largest consumer of electrical energy is refrigeration for butter storage (39%) and the largest consumers of thermal energy are the pasteuriser (56%), the clean-in-place (CIP) system (22%) and intake/separation/raw milk storage (22%). In many cases, the dairy processing factories reported the quantities of fuel types used (natural gas, fuel oil, coal, diesel, biogas, LPG, peat, etc.) rather than thermal energy. In these cases, calorific values were used to calculate the thermal energy, in kWh. Where combined heat and power (CHP) units were used, details of the annual quantity and type of fuel used, along with the resulting electrical and thermal energy, and details of any energy that was exported were specified. In some cases (e.g. homogenisation and blending), the individual energy consumption for the process was not reported and, therefore, is included in the last row of Table 2 as 'Other'.

Table 2: Reported electrical and thermal energy consumption during the manufacture of 1 kg of milk powder and 1 kg of butter

	Milk powder			Butter		
	Electrical (kWh)	**Thermal (kWh)**	**n**	**Electrical (kWh)**	**Thermal (kWh)**	**n**
Total energy	0.28 - 0.63	1.96 - 5.44	5	0.2 - 0.43	0.14 - 0.82	4
Intake/separation/raw milk storage	0.03 - 0.05	0.07 - 0.1	2	0.01 - 0.05	0.03 - 0.08	3
Pasteuriser	0.007 [a]	0.05 [a]	1	0.006 - 0.02	0.14 - 0.15	2
Butter churn	-	-	-	0.06 - 0.08	-	2
Evaporator	0.02 - 0.09	0.62 - 2.31	3	-	-	-
Dryer	0.08 - 0.12	0.99 - 2.68	3	-	-	-
Deaerator	-	0.12 [a]	1	-	-	-
Packaging	0.014 [a]	-	1	0.03 - 0.05	-	2
Refrigerator (butter storage)	-	-	-	0.14 - 0.29	-	2
Boilers	0.02 - 0.05	-	2	0.02 - 0.04	-	2
Clean in place (CIP) system	0.005 - 0.006	0.05 - 0.08	2	0.004 - 0.005	0.05 - 0.07	2
Tanker wash system	-	0.002 [a]	1	-	0.002 [a]	1
Air compressors	0.03 - 0.07	-	3	0.02 - 0.06	-	3
Wastewater treatment system	0.02 - 0.06	-	3	0.02 - 0.05	-	3
Administration	0.008 [a]	-	1	0.007 [a]	-	1
Other	0.04 - 0.1	-	2	0.04 - 0.08	-	2

[a] Energy consumption for the process reported by one dairy processing factory

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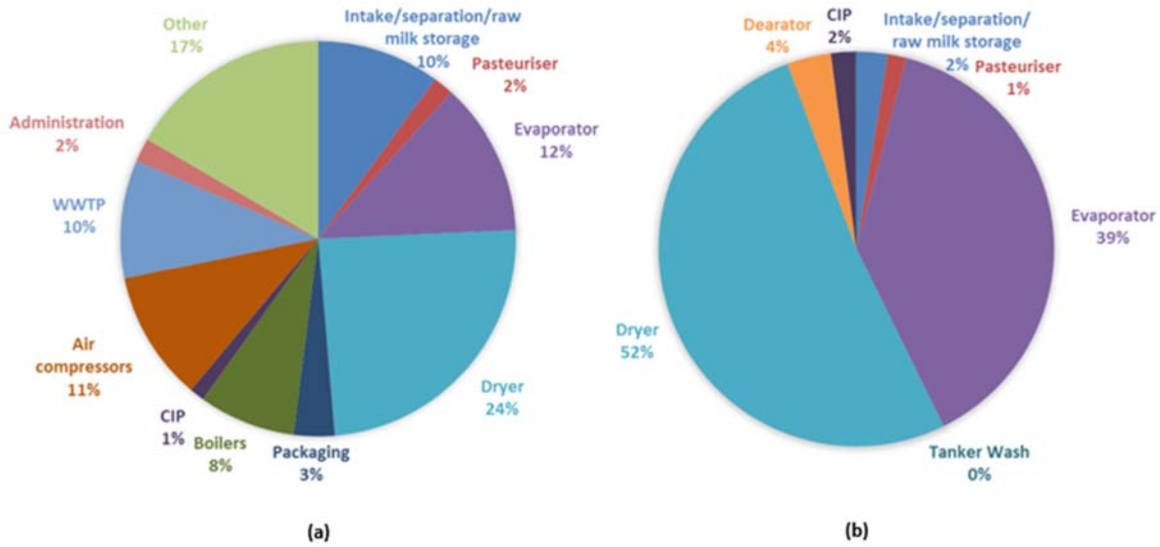

Figure 3: Breakdown of energy usage in milk powder manufacture, (a) electrical energy and (b) thermal energy

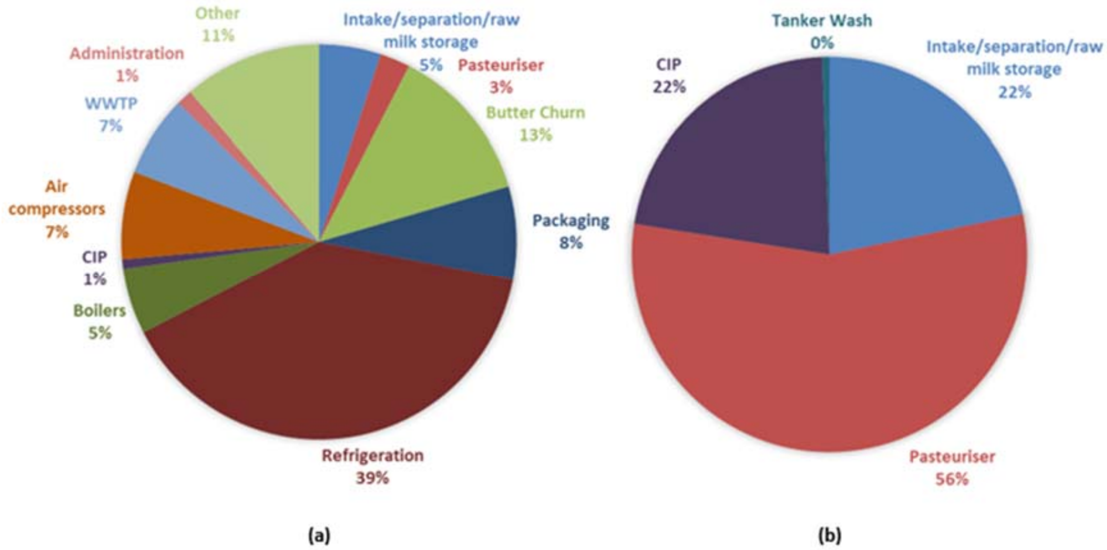

Figure 4: Breakdown of energy usage in butter manufacture, (a) electrical energy and (b) thermal energy

2.2.3 Water and chemical consumption

In Ireland, water used in dairy processing has three main sources: groundwater, surface water or public supply. The quantity of water consumed on-site, in cubic metres (m^3), and details of its source was reported within the survey of the dairy processing factories. The average water consumption reported by the dairy processing detailed in this study was found to be 1.21 L per L of milk processed, which is over 50% lower than the average water consumption for the Irish dairy processing industry in 2008 of 2.5 L per L of milk processed (Geraghty, 2011). A breakdown of water consumption of each of the main water users within the factory (e.g. CIP system, boiler feed, tanker wash etc.) was also requested. However, in many cases this was not available and, therefore, water statistics were

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reported on a whole-factory basis. The type of chemicals used (primarily sodium hydroxide and nitric acid in Ireland) and the quantity for the year was also reported on a whole-factory basis.

2.2.4 Packaging materials

The type of packaging used and the quantity of the individual finished packaged product have a significant effect on the overall environmental impact of a product's manufacture. These details were included in the survey of the dairy processing factories. However, if a factory didn't specify packaging material details, their products were assumed to be bulk packaged as 85% of Ireland's dairy products are exported (Enterprise Ireland, 2016). Therefore, in this analysis, where the packaging materials were not specified, bulk packaging was assumed, i.e. 0.014 kg of polypropylene sacks per kg product for milk powder and 0.03 kg of corrugated board per kg product for butter, which had been specified by dairy processing factories that included packaging material details.

2.2.5 Wastewater treatment

All of the dairy processing factories that were surveyed as part of this study had on-site wastewater treatment facilities. Therefore, operational wastewater treatment data was obtained in order to accurately model this process. Data relating to nutrient emissions to water, electrical energy consumption and chemical usage of the on-site wastewater treatment plant is detailed in Table 3. The types of chemicals used at the dairy sites surveyed included sulphuric acid, sodium hydroxide, polyaluminium chloride, aluminium sulphate, lime and polyelectrolyte. This site specific data was incorporated into an ecoinvent database Version 3 (Weidema et al., 2013) model for a wastewater treatment plant, class 2 and used in this study. On average, the GWP associated with dairy wastewater treatment was found to be approximately 4.43 kg CO_2 eq m^{-3} wastewater treated.

Table 3: On-site wastewater treatment details for surveyed dairy processing factories

	Unit	**Range**	**Mean (standard deviation)**	**n**
Wastewater treated	L wastewater/ L milk processed	0.536 - 1.566	0.934 (0.554)	3
Electricity consumption	MWh/L wastewater	3.57 - 4.92	4.35 (0.7)	3
Chemical usage	t/L wastewater	0.81 - 2.52	1.5 (0.9)	3
Emissions to water:				
Biological oxygen demand	mg/L wastewater	1 - 5.5	3.2 (2.2)	3
Chemical oxygen demand	mg/L wastewater	12.8 - 56	34.4 (30.6)	2
Suspended Solids	mg/L wastewater	3.174 - 5.651	4.021 (1.412)	3
Ortho-phosphates	mg/L wastewater	0.037 - 0.051	0.046 (0.008)	3

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Ammonia	mg/L wastewater	0.027 - 0.07	0.054 (0.023)	3
Total nitrogen	mg/L wastewater	2.792 - 6.362	4.055 (2.002)	3
Fats, Oils and Greases	mg/L wastewater	0.755 - 1.07	0.913 (0.222)	2

2.2.6 Solid waste disposal

The annual quantity of solid waste sent off-site for disposal was surveyed. The solid waste was reported as either hazardous or non-hazardous waste and categorised according to four different methods of disposal: landfill; incineration; recycling; and other. For the purpose of this analysis, a conservative assumption, that all solid waste reported as 'other' was disposed at a landfill site, was taken.

2.3 Allocation of inputs and emissions within dairy processing

The energy usage breakdown, specified in the survey by each dairy processing factory, is used to allocate energy usage between products. Where processes are common to two or more products or energy usage is reported on a whole-factory basis, mass allocation based on total solids is used to allocate energy between milk powder, butter and other dairy products in accordance with the guidelines in FIL-IDF (2015). In a number of cases, water consumption, chemical usage, wastewater and solid waste generation have been reported on a whole-factory basis and are allocated using the physico-chemical allocation matrix, which has been developed by Feitz et al. (2007), specifically for the dairy industry and advised by FIL-IDF (2010). However, as solid waste generation is not included in the physico-chemical allocation matrix, it is allocated between products using mass allocation based on total solids.

Since a detailed breakdown of energy usage within the dairy processing factories was obtained during this study, an effort is made to derive more suitable thermal and electrical energy allocation factors for butter processing in factories with few (i.e. two or three) products, which are normalised against milk powder similar to Feitz et al. (2007). The electrical energy allocation factor was found to be on average approximately 0.88 and the thermal energy allocation factor was found to be on average approximately 0.11. Based on these results, it is found that the physico-chemical allocation matrix over estimates the allocation factor for thermal energy and underestimates for electrical energy. This may be as a result of the matrix being designed for factories with a large number of products or a variation in processes in different countries, along with a variation of scale of the dairy processing factories used in the analyses. Nevertheless, further investigation is required.

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2.4 Life cycle impact assessment

The life cycle impact assessment (LCIA) methods used in this study are the IPCC 2013 GWP 100a, Cumulative Energy Demand and the ReCiPe Midpoint (H) (Goedkoop et al., 2009), which has also been used the study by Kim et al. (2013) of cheese and whey production in the USA. Consequently, the environmental impact categories that are analysed are: Terrestrial acidification potential (AP), kg SO_2 eq; Cumulative energy demand (CED), MJ; Freshwater eutrophication potential (FEP), kg P eq; Global warming potential (GWP), kg CO_2eq; Marine eutrophication potential (MEP), kg N eq; Water depletion (WD), m^3.

3 Results and discussion

3.1 Environmental impact assessment

The overall results of the environmental LCA are presented in Table 4, for each of the environmental impact categories. Of the life cycle stages, the processing of raw milk into milk powder and butter, which includes electrical and thermal energy usage, wastewater treatment system, process water consumption, chemical usage and solid waste generated, is the most significant contributor to each of the environmental impact categories. Since the majority of Irish dairy products are exported, products are bulk packaged, which requires less energy and raw materials. Therefore, packaging is the lowest contributor to each of the environmental impact categories in all instances, expect for the FEP and MEP associated with butter production. For many of the environmental impact categories, the impact associated with the manufacture of milk powder is significantly greater than the impact associated with the manufacture of butter. For example, the GWP associated with dairy manufacture is 1.482 kg CO_2 eq kg^{-1} milk powder and 0.528 kg CO_2 eq kg^{-1} butter, respectively. The impact categories concerned with eutrophication are approximately 30% greater for the manufacture of milk powder compared to butter, where FEP is 1.16×10^{-4} kg P eq kg^{-1} milk powder compared to 9.1×10^{-5} kg P eq kg^{-1} butter and MEP is 2.16×10^{-4} kg N eq kg^{-1} milk powder compared to 1.60×10^{-4} kg N eq kg^{-1} butter.

Table 4: Average results of the environmental impact assessment of milk powder and butter (per kg product)

	GWP kg CO_2 eq	CED MJ	FEP kg P eq	MEP kg N eq	AP kg SO_2 eq	WD m^3
Skim milk powder						
Raw milk transportation	0.112	1.93	1.12×10^{-5}	2.56×10^{-5}	4.53×10^{-4}	0.138

Processing [a]	1.38	20.18	9.3×10^{-5}	1.78×10^{-4}	4.69×10^{-3}	0.835
Packaging	0.028	1.04	9.27×10^{-7}	2.29×10^{-6}	7.91×10^{-5}	0.001
Total	1.52	23.15	1.05×10^{-4}	2.05×10^{-4}	5.22×10^{-3}	0.974
Full-fat milk powder						
Raw milk transportation	0.108	1.87	1.09×10^{-5}	2.48×10^{-5}	4.4×10^{-4}	0.134
Processing [a]	0.952	13.76	6.52×10^{-5}	8.66×10^{-5}	2.96×10^{-3}	0.592
Packaging	0.028	1.04	9.23×10^{-7}	2.28×10^{-6}	7.87×10^{-5}	0.001
Total	1.088	16.67	7.70×10^{-5}	1.14×10^{-4}	3.5×10^{-3}	0.727
Full cream milk powder						
Raw milk transportation	0.072	1.24	7.24×10^{-6}	1.65×10^{-5}	2.92×10^{-4}	0.089
Processing [a]	0.825	13.17	3.40×10^{-5}	3.83×10^{-5}	8.38×10^{-4}	0.268
Packaging	0.028	1.03	9.12×10^{-7}	2.26×10^{-6}	7.78×10^{-5}	0.001
Total	0.925	15.44	4.22×10^{-5}	5.71×10^{-5}	1.21×10^{-3}	0.358
Milk powder (average)						
Raw milk transportation	0.126	2.17	1.27×10^{-5}	2.89×10^{-5}	5.11×10^{-4}	0.156
Processing [a]	1.328	18.50	1.02×10^{-4}	1.85×10^{-4}	5.24×10^{-3}	0.953
Packaging	0.028	1.05	9.33×10^{-7}	2.31×10^{-6}	7.96×10^{-5}	0.001
Total	1.482	21.75	1.16×10^{-4}	2.16×10^{-4}	5.84×10^{-3}	1.109
Butter						
Raw milk transportation	0.117	2.01	1.17×10^{-5}	2.67×10^{-5}	4.73×10^{-4}	0.145
Processing [a]	0.379	4.76	6.34×10^{-5}	9.44×10^{-5}	1.48×10^{-3}	0.616
Packaging	0.032	0.42	1.55×10^{-5}	3.93×10^{-5}	1.28×10^{-4}	0.077
Total	0.528	7.22	9.06×10^{-5}	1.60×10^{-4}	2.08×10^{-3}	0.837

Legend: Terrestrial acidification potential (AP); Cumulative energy demand (CED); Freshwater eutrophication potential (FEP); Global warming potential (GWP); Marine eutrophication potential (MEP); Water depletion (WD)

[a] Processing includes electrical & thermal energy usage, wastewater treatment system, process water consumption, chemical usage and solid waste generated

Additionally, the results for milk powder manufacture has been aggregated into three types: skim milk powder, whole milk powder and full fat milk powder. It is important to note that not all of the milk powder products were manufactured in all dairy processing factories surveyed. From Table 4, it is clear to see that each milk powder product has a different environmental impacts. This is as a result of being manufactured in factories with different environmental impacts, as a result of efficiencies within the

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factory, rather than the processes involved in manufacturing each milk powder product. For example, the GWP associated with manufacturing full cream milk powder (0.925 kg CO_2 eq kg^{-1} milk powder) is lower than that of skim milk powder (1.52 kg CO_2 eq kg^{-1} milk powder). The reason for this is the factories manufacturing full cream milk powder have a lower environmental impact than those manufacturing skim milk powder. From examining the surveys, the main difference between the factories are associated with efficiencies resulting from economies of scale and the use of fuel with a low environmental impact (for example, natural gas compared to heavy fuel oil).

A breakdown of the contribution of the inputs and emissions to the total environmental impact for each of the impact categories associated with the manufacture of milk powder and butter is presented in Figure 5 and Figure 6, respectively. Energy contributes on average 89% and 78% of the total GWP, for milk powder and butter, respectively, for the life cycle stages assessed. Furthermore, energy contributes significantly to CED, AP and WD. Emissions associated with wastewater treatment contribute approximately 10% and 40% to the total FEP and MEP, respectively, for both milk powder and butter production. In addition, packaging materials is also a significant contributor these environmental impact categories for butter production.

The effect of solid waste disposal on a number of environmental impact categories (GWP of 4.8% & 5.6%, CED of 11.5% & 14.2% and AP of 3.4% & 4% for milk powder and butter, respectively) is evident in Figure 5 and Figure 6. As the majority of the solid waste is disposed of through recycling, these impacts are significantly reduced as recycling has a positive effect on the environment.

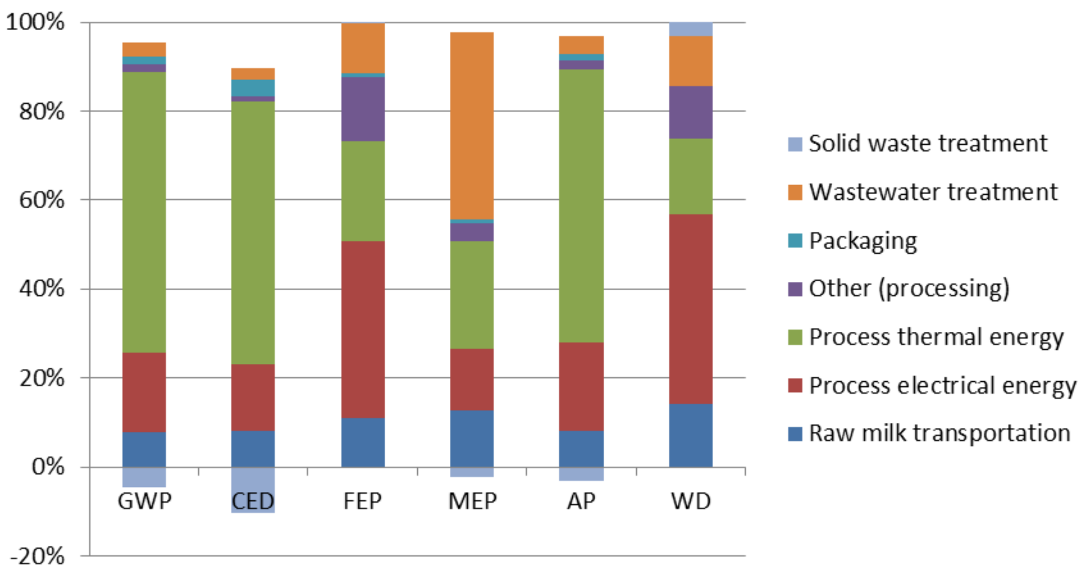

Figure 5: Contribution of the inputs and emissions to the total environmental impact of milk powder

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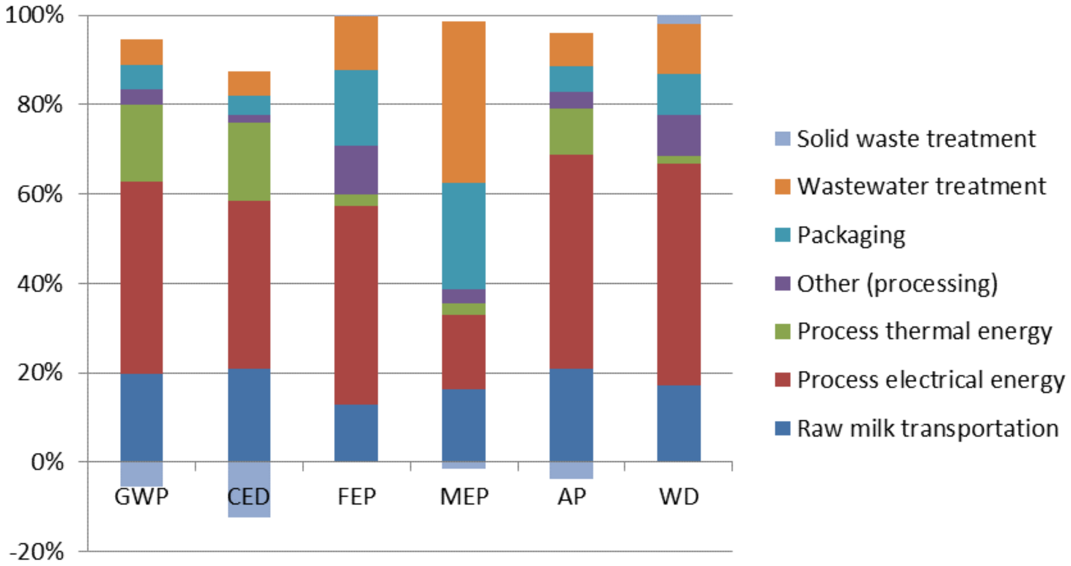

Figure 6: Contribution of the inputs and emissions to the total environmental impact of butter

3.2 Uncertainty analysis

An uncertainty analysis was performed, as part of the impact assessment, to determine the variability of the LCI data and how it affects the reliability of the results of the LCIA. Each Monte Carlo simulation used randomly selected values for inputs, outputs and emissions according to a lognormal probability distribution, which was also employed by Broekema and Kramer (2014).

The mean, standard deviation and coefficient of variation (CV), which are given as 'Basic CV' for each product in Table 5, was obtained from the results of the surveyed data. In order to include uncertainty of data quality in the analysis, the CV was modified for each of the inputs and emissions, included in Table 5, based on six criteria of the data: reliability, completeness, temporal correlation, geographic correlation, future technological correlation and sample size. This modification was performed using the process outlined in Weidema and Wesnæs (1996) and the pedigree matrix, along with the uncertainty factors, specified in Ciroth et al. (2013). In this analysis, it is assumed that the environmental impact data is constant and only the uncertainty associated with the inputs and outputs are considered. The basic CV, uncertainty from each of the six criteria for each input and emission and the modified CV for milk powder and butter are summarised in Table 5. The majority of the data used was obtained from the survey of dairy processing factories in Ireland. However, in some instances, where data was omitted, average values were used.

Table 5: Basic CV, uncertainty and modified CV used in the analysis for milk powder and butter

	Raw milk transportation	Electricity	Fuel	Other (process)	Packaging	Wastewater	Solid waste

Basic CV							
Milk powder	35.6	50	52.4	27.8	1.5	73	117.5
Butter	38.9	73.3	75.4	84.6	30.6	44	110.4
Uncertainty							
Reliability	1.05	1.0	1.0	1.05	1.05	1.0	1.0
Completeness	1.02	1.02	1.02	1.05	1.05	1.02	1.02
Temporal correlation	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Geographic correlation	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Future technological correlation	1.0	1.0	1.0	1.2	1.0	1.2	1.0
Sample size	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Modified CV							
Milk powder	36	50	52.5	35	7.2	75.7	117.6
Butter	39.3	73.3	75.5	87.2	31.4	48.4	110.4

The LCA results, presented in Section 3.1, are analysed using 1,000 Monte Carlo simulations and the results of these simulations are given in Table 6. For each Monte Carlo simulation, each of the inputs and emissions associated with the product was randomly varied using a lognormal distribution, which was based on the average values from the survey and modified CV given in Table 5. The mean, CV and 95% confidence interval ranges of each of the environmental impact categories from the uncertainty analysis are presented in Table 6. GWP is an impact of notable interest where the ranges are found to be 0.68-2.894 kg CO_2 eq kg^{-1} milk powder and 0.251-0.996 kg CO_2 eq kg^{-1} butter. The ranges for the other categories follow a similar positively skewed distribution about the mean.

Table 6: Results of 1,000 Monte Carlo simulations for uncertainty analysis of milk powder and butter (per kg product)

	Unit	Mean	Coefficient of variation (CV) (%)	95% confidence interval (CI)	
Milk powder					
Global warming potential	kg CO_2 eq	1.403	40.3	0.68	2.894
Cumulative energy demand	MJ	20.4	46.4	9	46.2
Freshwater eutrophication	kg P eq	1.15 x10^{-4}	25.3	7.1 x10^{-5}	1.85 x10^{-4}

Marine eutrophication	kg N eq	2.15×10^{-4}	37.9	1.08×10^{-4}	4.28×10^{-4}
Terrestrial acidification	kg SO_2 eq	0.0056	37.3	0.0028	0.011
Water depletion	m^3	1.09	25.4	0.68	1.77
Butter					
Global warming potential	kg CO_2 eq	0.5	38	0.251	0.996
Cumulative energy demand	MJ	6.7	48.8	2.9	15.7
Freshwater eutrophication	kg P eq	8.7×10^{-5}	32.5	4.8×10^{-5}	1.58×10^{-4}
Marine eutrophication	kg N eq	1.59×10^{-4}	25.1	9.9×10^{-5}	2.56×10^{-4}
Terrestrial acidification	kg SO_2 eq	0.002	38.9	0.001	0.004
Water depletion	m^3	0.79	35.3	0.42	1.52

3.3 Comparison with international studies

There is a limited number of papers available which discuss milk powder and butter processing and these only explore the impact on climate change. Therefore, the GWP results of the presented analysis (Table 4) have been compared to the results of Sheane et al. (2011), which estimated the carbon footprint associated with the Scottish dairy supply chain, Flysjö (2012), which estimated the carbon footprint of milk and dairy product chains using data from a European company, and Finnegan et al. (2015), where a macro-scale study assessing the GWP associated with dairy products produced in the Republic of Ireland was performed.

3.3.1 Milk powder comparison

The processing of raw milk into milk powder is the most significant contributor to GWP, of the life cycle stages assessed, at 1.328 kg CO_2 eq kg^{-1} milk powder, which is lower than a previous estimate (Finnegan et al., 2015) of 1.824 kg CO_2 eq kg^{-1} milk powder. One of the main reasons for this difference is the allocation of inputs and emissions between a large number of products in Finnegan et al. (2015) and between two main products in the present study. Where possible, the results from a detailed survey of the dairy processing factories was used to allocation between the two main products. However, when there was insufficient data, the same allocation method employed in Finnegan et al. (2015) was used in the current analysis. Therefore, the results of the present study yield a more accurate estimation of the environmental impacts of manufacturing milk powder and butter in Ireland.

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Conversely, the value for processing found in the current analysis is greater than the Flysjö (2012) study for skim milk powder of 0.74 kg CO_2 eq kg^{-1} milk powder, which only accounts for energy usage. Even if only process energy usage was accounted in the present study, the contributor to GWP would be 1.32 kg CO_2 eq kg^{-1} milk powder as the processing of powdered products is highly energy intensive. When comparing the results from Flysjö (2012) to the range of the 95% confidence interval, presented in Section 3.2, it is less than the lower bound (0.902 kg CO_2 eq kg^{-1} milk powder). A possible reason for this discrepancy is that the study of Flysjö (2012) deals with one large company (Arla Foods, which is the seventh largest dairy company in the world) where efficencies of scale would incur lower impacts relating to producing the product when compared to smaller dairy processing factories (i.e. the ones used in this study).

Raw milk transportation accounted for 0.126 kg CO_2 eq kg^{-1} milk powder, which is greater than Finnegan et al. (2015) of 0.047 kg CO_2 eq kg^{-1} milk powder. The dairy processing factories included in the survey reported an average distance per raw milk collection route of 169 km, which is much greater than the value specified by Quinlan (2013) of 79 km. The GWP associated with packaging of the final product is 0.028 kg CO_2 eq kg^{-1} milk powder, where the majority of milk powder is bulk packaged for export, is much lower than reported by Flysjö (2012) (0.73 kg CO_2 eq kg^{-1} packaging milk powder) for skim milk powder in a 900g container. This difference highlights the significant effect that packaging can have on the environmental impact of a dairy product.

3.3.2 Butter comparison

Similar to milk powder production, the processing of raw milk into butter is the most significant contributor to GWP, of the life cycle stages assessed, at 0.379 kg CO_2 eq kg^{-1} butter. This value is greater than the estimate by Sheane et al. (2011) of 0.06 kg CO_2 eq kg^{-1} butter and lower than the estimate of Finnegan et al. (2015) of 0.415 kg CO_2 eq kg^{-1} butter. Additionally, the present value is marginally greater than the estimate by Flysjö (2012) of 0.35 kg CO_2 eq kg^{-1} butter. However, since Flysjö (2012) only accounts for energy usage, if the same is done in the present study, the contributor to GWP would be 0.35 kg CO_2 eq kg^{-1} butter, which is the same as the estimate by Flysjö (2012). In the present analysis, the remainder of the GWP is contributed by wastewater treatment, solid waste treatment, water consumption and chemical usage, which is illustrated in the breakdown in Figure 6.

The GWP associated with the transportation of raw milk to the dairy processing factory is estimated 0.117 kg CO_2 eq kg^{-1} butter, which is greater than the estimate by Sheane et al. (2011) of 0.07 kg CO_2 eq kg^{-1} butter and the estimate of Finnegan et al. (2015) of 0.041 kg CO_2 eq kg^{-1} butter. Similar to milk powder production, the majority of butter is bulk packaged for export and, therefore, the estimate in

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this study (0.032 kg CO_2 eq kg^{-1} butter) is much lower than reported by Sheane et al. (2011) of 0.14 kg CO_2 eq kg^{-1} butter and Flysjö (2012) of 0.38 kg CO_2 eq kg^{-1} butter, in a 250g container.

3.4 Future of a changing landscape in Ireland

Over the next decade a number of the environmental impact categories, included in this study, may have a significant influence on the Irish dairy processing industry, mainly GWP, FEP, MEP and WD.

As Ireland's agricultural and agri-food sector continues to grow, it has been suggested that a carbon tax on dairy processors, similar to the carbon tax paid by motorists for their cars and householders for their fuel bills, may be introduced as an incentive to reduce emissions (Melia, 2015). It is evident in this study that energy consumption is the most significant contributor to GWP. Therefore, it is imperative that energy use within the plants is accurately determined in future studies and targeted measures to reduce energy consumption identified, as these will be key to reducing the GWP associated with dairy products. On the other hand, the use of renewable sources of energy in place of fossil fuels would also lead to reduction in the GWP of products.

At current milk processing levels, many dairy processors in Ireland are at the limits of their emissions to water, as set by the Irish environmental protection agency (EPA). As a result of the increase in raw milk production, processors will be under increased pressures to remain within these limits. Therefore, an increase in energy and resources will be required in many on-site wastewater treatment facilities, which will increase the environmental impact of the process. In this case, the direct contribution to eutrophication (FEP and MEP) may be maintained but the indirect contribution, as a result of an increase in energy and resources, would be increased. Therefore, an overall increase in eutrophication over the whole life cycle would result.

In 2015, domestic water charges were introduced in the Republic of Ireland for the first time. Even though this didn't affect the Irish dairy processing industry, as groundwater and surface waters are the main source, it may in the future if extraction charges are introduced. Therefore, water conservation and the overall reduction in on-site water consumption is generating greater interest within the sector.

4 Conclusion

In this study, the environmental impacts associated with the manufacture of milk powder, which includes skim milk powder, whole milk powder and full fat milk powder, and butter in the Republic of Ireland, from raw milk transportation to the processing factory, processing of raw milk into each product and packaging of the final product, is estimated through LCA. Additionally, the results of this study will serve as a benchmark for the Irish dairy processing industry as individual processors can evaluate their performance in comparison. As there is limited information available relating to the environmental impacts associated with manufacture of milk powder and butter, mainly concerned with energy usage and GWP, it will serve as an international benchmark also.

This analysis can be used to identify opportunities to reduce the negative environmental impacts of the Irish dairy processing industry. From the breakdown of the contribution of the inputs and emissions to the total environmental impact of milk powder and butter (Figure 5 and Figure 6, respectively), it is evident that energy usage is overall the most significant contributor to negative environmental impacts. Therefore, increased efficiency of milk transportation, including the optimisation of collection routes to reduce fuel consumption, would help to reduce its negative environmental impacts. Within the factory, evaporators and dryers, for milk powder manufacture, with increased energy efficiency and low-energy refrigeration systems, for butter storage, should be targeted to reduce the negative environmental impacts of the dairy processing industry.

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