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Environmental impacts of ice cream

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ABSTRACT

Ice cream is consumed daily worldwide and yet its environmental impacts are scarcely known. This paper presents a first comprehensive life cycle assessment of market-leading vanilla and chocolate ice creams, considering both regular and premium products. The results suggest that their impacts are broadly similar across the 18 impact categories considered. For the majority of the impacts, chocolate regular ice cream is a slightly better option than the other varieties. Overall, the regular versions of the product have lower environmental impacts than the premium. Raw materials contribute most to the majority of impacts (>70%). The exception is ozone depletion, which is mainly due to refrigerated storage at the retailer (95%). The impacts are highly sensitive to the duration of storage and the type of refrigerant. Furthermore, the global warming potential of chocolate ice cream is very sensitive to land use change associated with cocoa beans cultivation, increasing the impact by 60%. Considering annual consumption of ice cream in the UK, the total primary energy demand contributes to 3.8% of energy consumption in the whole food sector while greenhouse emissions contribute 1.8%. Future improvements in the supply chain should focus on milk and cocoa production, reduced storage time and types of refrigerant used. Product reformulation to reduce the amount of milk (fat) and sugar should also be considered, in line with the emerging health-driven market trends. In addition to industry and policy makers, the findings of this study will be of interest to consumers, enabling them to make better choices with respect to environmental impacts of most popular ice creams.

1. Introduction

Food is essential for life, but it also causes extensive environmental impacts. For instance, food production and consumption contribute 19%–29% of the global greenhouse gas emissions (Vermeulen et al., 2012). Across a broader range of environmental impacts, food has been estimated to contribute at least 20%–30% of the total impacts within Europe (Tukker et al., 2006). At the same time, the FAO (2015) forecasts a global increase in food consumption by almost 4% by the year 2030.

The food sector is also one of the most important economic contributors across the globe. For example, the food and drink sector in the UK had a turnover of £95 bn in 2013, accounting for 18.3% of the total industrial production by turnover (FDF, 2015). Due to its environmental and economic importance, a range of overarching strategies have already been identified in the sector (DEFRA, 2014) aimed at decreasing environmental burdens, such as greenhouse gas emissions, waste generation, as well as water and energy consumption.

Within the food sector, ice cream is one of the most popular 'luxury' items worldwide and the sector is growing fast. For instance, the UK market is predicted to grow by 7.4% in the period 2015–2018 (Key Note, 2015). By the end of 2019, it is anticipated that the sales value of ice cream will reach £1.24 bn. Vanilla and chocolate ice cream are the leading flavours, occupying nearly 36% of the total market share, with around 18% each (Key Note, 2015).

Apart from flavour and recipe variations, ice cream can also be divided into further sub-categories, such as take-home and wrapped ice cream (Key Note, 2015), the latter of which are intended for immediate consumption (Foster et al., 2006). The take-home category includes ice cream packaged in a plastic tub, commonly sold in supermarkets. In the UK, for example, this type of product accounts for 43% of total ice cream sales (Mintel, 2015).

Several studies of environmental impacts of common ice-cream ingredients are available (Foster et al., 2006; Hogaas, 2002; Hospido et al., 2003; Nutter et al., 2013; Thomassen et al., 2008). However, there is only a limited number of studies of ice cream, all focusing

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on the global warming potential (GWP). One of these (Scottish Government, 2011) estimated the GWP of ice cream at 4 kg CO_2 eq./kg. The company Ben & Jerry also reported a similar figure (3.36 CO_2 eq./kg) for a plain ice cream (Ben and Jerry, 2016; Garcia-Suarez et al., 2006). A further study (Foster et al., 2006) reported a much smaller value of 0.97 kg CO_2 eq./kg, probably because it did not consider the retail, consumption and waste treatment stages.

Therefore, the wider environmental impacts of ice cream are currently unknown. In an attempt to fill this knowledge gap, this paper considers life cycle environmental impacts of two market-leading flavours of ice cream: vanilla and chocolate. Both regular and premium products are evaluated. The analysis is carried out first at the level of individual products and then at the sectoral level, focusing on consumption of ice cream in the UK. Extensive sensitivity and uncertainty analyses have also been carried out to ensure that the results are robust. Various improvement opportunities are also discussed, targeting environmental hotspots. As far as the authors are aware, this is the first study of its kind internationally. The following sections detail the methods, data and assumptions used in the study.

2. Methods

Life cycle assessment (LCA) has been used to evaluate the environmental sustainability of the ice cream supply chain, following the ISO 14040/14044 standards (ISO, 2006a; ISO, 2006b). Goal and scope of the study are described below, followed by the inventory data and the impact assessment method used in the study.

2.1. Goal and scope of the study

The main goal of the study is to quantify the environmental impacts of ice cream produced and consumed in the UK. A further aim is to identify environmental hotspots and opportunities for improvements along the supply chain. The functional unit is defined as "1 kg of ice cream consumed at home". Four different product types are considered with differing compositions and flavours. They are as follows:

- vanilla regular;
- vanilla premium;
- chocolate regular; and
- chocolate premium.

These flavours have been selected based on their aforementioned leading position in the market. The distinction between the 'regular' and 'premium' products is made to represent better a market with considerable product quality and cost diversity.

The product formulation of the four types of ice cream considered is given in Table 1. As can be seen, the 'premium' variety has a higher content of milk fat and sugar and it also contains eggs. A further distinction for the vanilla flavour is that the premium ice cream contains vanilla, while the regular has a flavouring agent (vanillin). The premium chocolate variety has also more cocoa powder than its regular equivalent.

The scope of the study is from cradle to grave. As outlined in Fig. 1, the main life cycle stages considered are: production of ingredients, ice cream manufacturing and packaging, distribution to and storage at the retailer, consumption at home and end-of-life waste management. As also indicated in the figure, all intermediate transport and waste management activities are considered in the study. The following sections provide further details on each of these life cycle stages.

2.2. Inventory data

Life cycle inventory (LCI) data have been sourced from manufacturers and literature. The background LCI data are mainly from Ecoinvent V2.2 (Ecoinvent, 2010). The data for each life cycle stage are detailed below.

2.2.1. Raw materials (ingredients)

As detailed in Table 2, ice cream ingredients include milk, cream, sugar, vanilla extract (premium vanilla ice cream), vanillin (the regular version), cocoa powder (chocolate flavour), eggs (premium products) and water. The sources of life cycle inventory (LCI) data for each ingredient can also be found in Table 2.

Raw milk is produced in the UK, containing 4% fat (Scottish Government, 2011; Williams et al., 2006). It is processed to produce cream (10% w/w) and skimmed milk (90% w/w). All the cream and some of the produced skimmed milk are used in the production of ice cream, with the rest of the latter used elsewhere. The cream contains 40% fat and the skimmed milk 0.5%. To be used for ice cream production, they each must contain 9.5% non-fat milk solids (Scottish Government, 2011). While the cream already meets this requirement, skimmed milk must be processed further to concentrate it (as discussed further in the next section).

Sugar is assumed to be the only sweetener used in all the ice cream products. Around 40% of sugar is from sugar beet produced in the UK and the rest from sugar cane imported from Brazil and refined in the UK (DEFRA, 2006a). Vanilla beans are cultivated in Madagascar before being transported to the UK for processing into vanilla extract (Audsley et al., 2009). Vanillin is assumed to be produced in the UK. Cocoa beans are cultivated in Ghana and processed to cocoa powder in the UK (Audsley et al., 2009). Egg yolk (pasteurised) is used for vanilla ice cream.

Stabilisers and emulsifiers are also used in the production of ice cream but they are not considered in the study due to a lack of data. However, as shown in Table 2, they account for less than 0.5% of the mass of the products and, therefore, are not expected to cause significant impacts.

Table 1
Ice cream formulations considered in the study (Marshall et al. (2003).

Ingredient	Vanilla regular (%)	Vanilla premium (%)	Chocolate regular (%)	Chocolate premium (%)
Milk fat	10	16	10	16
Non-fat milk solids	11	8.5	12	8
Sugar	15	17	16	19
Vanillin[a]	0.365			
Vanilla		0.365		
Cocoa powder			3	3.5
Egg-yolk		1.4		1.4
Stabiliser – emulsifier	0.04		0.3	
Water	63.60	56.74	58.7	52.1

[a] Vanillin is assumed as flavouring ingredient in the regular vanilla ice cream due to its low price relative to vanilla.

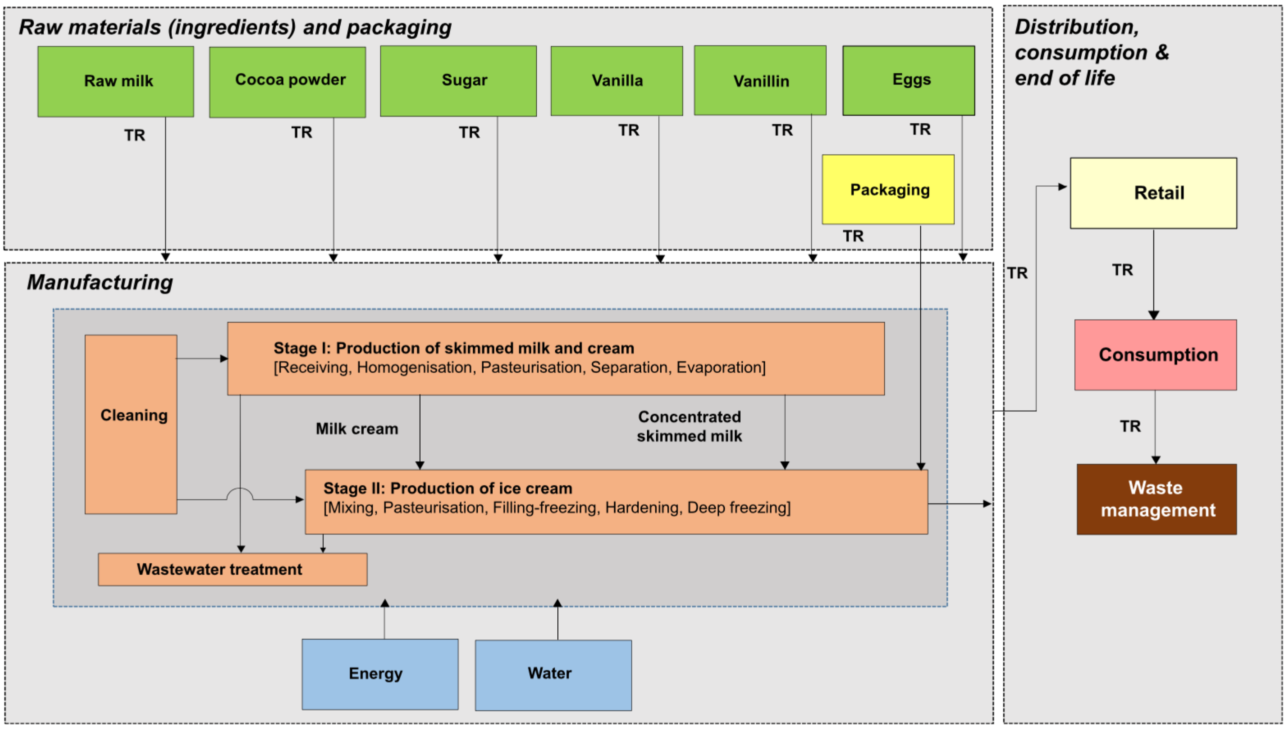

Fig. 1. The life cycle of ice cream considered in the study.

Table 2
Inventory data for raw materials (ingredients).

Ingredient	Vanilla regular (kg/kg)	Vanilla premium (kg/kg)	Chocolate regular (kg/kg)	Chocolate premium (kg/kg)	Country of origin	Data source
Raw milk[a]	2.5	2.5	4	4	UK	Scottish government (2011); Ecoinvent (2010)
Cream	0.25	0.40	0.25	0.40		
Milk to produce concentrated skimmed milk	1.07	0.706	1.18	0.649		
Concentrated skimmed milk	0.596	0.415	0.557	0.36		
Sugar	0.15	0.17	0.16	0.19	UK (sugar beet) Brazil (sugar cane)	Ecoinvent (2010); Klenk et al. (2012) Ecoinvent (2010)
Vanilla extract		3.65×10^{-3}	–	–	Madagascar	Williams et al. (2006)
Vanillin	3.65×10^{-3}					Borregard (2010)
Cocoa powder	–	–	0.03	0.035	Ghana	EC (2015a)
Egg yolk (pasteurised)	–	0.014	–	0.014	UK	UBA (2016) [b]; EC (2015b) [c]
Stabilisers and emulsifiers	0.004	0.001	0.003	0.001	UK	Excluded due to a lack of data

[a] Total amount of raw milk used for the production of cream and skimmed milk.
[b] Egg production at farm.
[c] Pasteurisation.

2.2.2. Manufacturing

It is assumed that raw milk processing and ice cream manufacturing take place in the same industrial facility, with the former referred to here as 'Stage I' and the latter as 'Stage II'. The inventory data for both stages are summarised in Table 3.

Raw milk processing (Stage I) involves clarification and storage, homogenisation and pasteurisation, followed by separation into milk cream and skimmed milk. The latter is concentrated in an evaporator and mixed in Stage II with the rest of the ingredients, followed by their pasteurisation. The mix is then cooled to room temperature and poured into plastic boxes while being simultaneously frozen. At this stage, air is also injected into the mix to gain volume and take on the well-known texture of ice cream. The ice cream is then hardened, packed into secondary packaging and stored in a deep freezer (Marshall et al., 2003). The amounts of refrigerant used and the frozen-storage times are shown in Table 4. The assumed refrigerant is liquid ammonia for which the LCI data have been obtained from Ecoinvent (2010).

Electricity LCI data correspond to the UK electricity mix; steam is produced using natural gas. It is assumed that 2% of ingredients are lost during the manufacturing process (UNEP, 1996) and are discharged with wastewater from cleaning activities.

2.2.3. Packaging

As shown in Table 5, primary, secondary and tertiary packaging used for the ice cream has been considered as well as shopping

Table 3
Manufacturing processes used in processing of raw milk and ice cream production.

Process[a]	Steam (MJ/kg)	Electricity (MJ/kg)	Data source
Stage I: Milk processing			
Receiving			
Clarification		0.02	Brush et al. (2011)
Storage		0.042	~II~
Homogenisation		0.0233	~II~
Pasteurisation	0.213		~II~
Separation		0.0035	~II~
Concentration	0.328	0.07	~II~
Stage II: Ice cream production			
Mixing		0.02	Brush et al. (2011)
Pasteurisation	0.214		~II~
Cooling		0.197	~II~
Filling, freezing		0.18	Manufacturer (confidential)
Hardening		1.2	Brush et al. (2011)
Packing	0.034 (petrol)		~II~
Deep freezing[b]		1.45	Tassou et al. (2008)
Cleaning activities[c]		0.105	Hogaas (2002); DeJong (2013); Ecoinvent (2010)
Site utilities			
Lighting		0.33	UBA (2016)
Heating	0.068		~II~

[a] The processes based on Marshall et al. (2003).
[b] Average energy consumption for frozen products (Tassou et al., 2008).
[c] Includes cleaning in place for both Stage I and Stage II. The amount of water used for cleaning is 2.7 kg/kg ice cream produced (Envirochemie, 2016).

Table 4
Refrigerant quantity and storage time in manufacturing (Stage II).

Process	Refrigerant (mg/kg-day)	Storage time (days)	Data source
Freezing	17.59	N/A[a]	Schmidt Rivera et al. (2014)
Hardening	174[b]	2 days	Schmidt Rivera et al. (2014); Marshall et al. (2003)
Deep freezing	174[b]	30 days	Schmidt Rivera et al. (2014); Marshall et al. (2003)

[a] There is no storage as the freezing and filling processes take place simultaneously.
[b] Refrigerant loss of 15% per annum is considered, assuming walk-in freezers (Tassou et al., 2008).

bags used by consumers. Polypropylene tub is considered for the primary packaging as the most-widely used material for manufactured ice cream in the UK. It is assumed that raw milk and sugar are transported in bulk to the manufacturer and thus no packaging is considered for these two ingredients. The packaging for the rest of ingredients is also excluded as their quantities per functional unit are small and hence unlikely to have much bearing on the impacts.

2.2.4. Retail

It is assumed that the ice cream is distributed from manufacturer directly to retailer, where it is stored in a freezer for one week before being purchased by the consumer (Marshall et al., 2003). Energy consumption by the freezer and site utilities (lighting and heating) have been calculated according to Tassou et al. (2008). The assumed type of refrigerant is R134a, with an annual leakage rate of 15% (Tassou et al., 2008). The inventory data are summarised in Table 6.

2.2.5. Consumption

This stage comprises refrigerated storage and consumption at home as well as cleaning of the dishes used to eat the ice cream. According to Foster et al. (2006), ice cream remains in the household freezer for one month on average. Therefore, the electricity consumption is based on that duration and the volume of the freezer occupied, as detailed in Table 7. The refrigerant leakage is not considered as domestic freezers do not leak (Tassou et al., 2008). It is assumed that all the ice cream is consumed.

The dishes are assumed to be cleaned in a dishwasher of energy category A (Siemens, 2015). The consumption of energy, water and detergent attributable to the ice cream is based on the volume of space occupied by the cups and spoons as a proportion of the total internal dishwasher volume (Table 7). All LCI data in the consumption stage have been sourced from Ecoinvent (2010).

2.2.6. Waste management

These data are summarised in Table 8. The modelling of waste streams has been performed based on the UK waste management

Table 5
Packaging used for ice cream per kg of ice cream.

Material	Primary (g/kg)	Secondary[a] (g/kg)	Tertiary (g/kg)	Plastic bag[b] (g/kg)	Data source
Polypropylene (tub)	75				Own measurements
Cardboard (box)		33			Ecoinvent (2010)
Low density polyethylene (film)			4.7	2.5	EC (2016); Ecoinvent (2010)

[a] There are six tubs per one cardboard box.
[b] The plastic bag weighs 7.5 g and has a volume of 6 l. Since 1 kg ice cream in a tub has a volume of 2 l, 2.5 g of the plastic bag is allocated to 1 kg of ice cream.

Table 6
Refrigerant and energy used in the retail stage.

Activity	Energy consumption (MJ/kg-day)	Refrigerant charge (mg/kg-day)	Storage time (days)	Data source
Refrigeration	0.065[a]	28.5[b]	7	Tassou et al. (2008), Marshall et al. (2003)
Site utilities (lighting, heating)	0.0006[c]			Tassou et al. (2008)

[a] Remote, horizontal, open, frozen refrigeration systems (RHF4) are assumed for frozen storage. The energy consumption per kg-day is estimated considering the weekly ice cream throughput per 1 m^2 display area (200 kg) and the average energy consumption (91 kWh/m^2-week) of the system (Tassou et al., 2008).
[b] Estimated considering the average refrigerant charge (3.5 kg/kW), a total display area (TDA) equal to 2.71 m^2 (BSI, 2015), the power of the system (4 kW) and the weekly load of ice cream (200 kg).
[c] Typical energy consumption attributable specifically to frozen products (Tassou et al., 2008).

Table 7
Data for the consumption stage.

Activity	Description
Refrigerated storage at consumer	Storage time: 30 days Energy consumption: 6.8 kWh/kg ice cream (whole fridge: 0.8 kWh/day) Volume of deep freezer: 235 l
Dishwashing	Dishwasher energy class: A Temperature: 40 °C Volume of the dishwasher: 260 l Bowls and spoons total volume: 2 l Energy consumption: 5.6 Wh/kg ice cream (0.74 kWh per cycle) Water consumption: 0.0722 l/kg ice cream (9.5 l per cycle) Detergent: 0.076 g/kg ice cream (10 g per washing cycle)

practice. The inventory data for landfilling, incineration, recycling and wastewater treatment activities have been obtained from Ecoinvent (2010). The system has been credited for the energy recovered from incineration of waste packaging.

2.2.7. Transport

As ice cream requires refrigerated transport, the consumption of refrigerants and additional fuel usage must be accounted for; these data have been sourced from Tassou et al. (2009) and are given in Table 9. The assumed annual leakage of refrigerant is 23.6% (Tassou et al., 2008). The refrigerant used for transport is considered to be R134a and the LCI data for its production have been sourced from Ecoinvent.

A summary of all transport modes and distances throughout the life cycle is presented in Table 10. Transport distances for the raw materials are based on the origin of the ingredients, as mentioned previously. The distance travelled by the consumer to purchase the ice cream has been calculated according to Pretty et al. (2005), while the transport distances of commercial and municipal waste to recycling, incineration or landfill have been estimated according to Amienyo (2012), using inventory data from Ecoinvent (2010). In cases where transport LCI data were not available for the UK, the European average has been used or, if that was unavailable, Swiss conditions have been assumed (as in Ecoinvent).

2.2.8. Allocation

Economic allocation has been used for the milk and egg co-products, following the ISO guidelines (ISO, 2006b). Wholesale prices have been used for the milk co-products (DairyCo, 2015), as detailed in Table 11. Due to a lack of information on the wholesale price of skimmed milk, this value has been approximated by using the raw milk wholesale price at the farm gate and increasing it by 35% to account for the average manufacturers' profit margin (DairyCo, 2015).

2.3. Impact assessment

The environmental impacts have been estimated using the ReCiPe midpoint method (Goedkoop et al., 2013) as implemented in GaBi V6.4 (Thinkstep AG, 2016). The impact categories considered in the study are: global warming potential (excluding biogenic carbon), ozone depletion, fossil fuel depletion, freshwater

Table 8
Data for waste management.

Waste type	Amount (g/kg)	Treatment type	Data source
Polypropylene (tub)	75	58% landfill, 34% incineration with energy recovery (heat and electricity) and 8% incineration without energy recovery	EC (2015c)
Corrugated cardboard (box)[a]	33	86.5% recycling and 13.5% incineration with energy recovery	EC (2015d)
Plastic bags (consumer)	2.5	58% landfill, 34% incineration with energy recovery and 8% incineration without energy recovery	EC (2015c)
Low density polyethylene		86.5% recycling and 13.5%	EC (2015d)
Wastewater (manufacturing)	2.7	Wastewater treatment	Envirochemie (2016); UBA (2005)
Wastewater (dishwasher)	0.072	Wastewater treatment	Envirochemie (2016); UBA (2005)

[a] The rate of recycling of corrugated-board is 90% (Ecoinvent, 2010).

Table 9
Fuel consumption during refrigerated transport and refrigerant charge.

Activity	Amount (l/kg-km)	Amount (mg/kg-km)	Source of data
Additional fuel for the refrigeration unit[a]	1.61×10^{-5}		Tassou et al. (2009)
Refrigerant charge		0.176	Schmidt Rivera et al. (2014)

[a] Estimated considering diesel consumption of the refrigeration unit in a medium rigid vehicle (Tassou et al., 2009).

Table 10
Transport data.

Life cycle stage	Transport step	Country of origin	Transportation means	Distance (km)
Raw materials	Milk	UK	Lorry (16–32 t)	200
	Sugar			
	from sugar beet	UK	Lorry (16–32 t)	200[a]
	from sugar cane			
	by road	Brazil	Lorry (16–32 t)	500[a]
	by sea	Brazil to UK	Freight ship	9650
	by road	UK	Lorry (16–32 t)	200[a]
	Vanillin	UK	Lorry (16–32 t)	200
	Vanilla			
	by sea	Madagascar to UK	Freight ship	9058
	by road	UK	Lorry (16–32 t)	200
	Cocoa beans			
	by sea	Ghana to UK	Freight ship	7370
	by road	UK	Lorry (16–32 t)	200
	Eggs	UK	Lorry (16–32 t)	200
Retail	Ice cream to retailer	UK	Lorry (3.5–7.5t)	150[a]
Packaging	Packaging to manufacturer	UK	Lorry (16–32 t)	200[a]
	Plastic bags to retailer	UK	Lorry (16–32 t)	200
Consumption	Product to consumer	UK	Car (petrol)	0.135[b]
End-of-life waste management	Waste to recycling plant	UK	Lorry (7.5–16 t)	100
	Waste to landfill	UK	Lorry (21 t)	30
	Waste to incineration	UK	Lorry (21 t)	30

[a] Transport assumptions based on typical commodity product distances (EC, 2016).
[b] Average roundtrip distance of 6.4 km divided by 28 kg of average shopping weight; 59% of distance travelled by car on average (Pretty et al., 2005).

Table 11
Data for allocation between milk co-products for different types of ice cream.

Co-products	Wholesale price (£/kg)	Vanilla regular (kg/kg)	Vanilla premium (kg/kg)	Chocolate regular (kg/kg)	Chocolate premium (kg/kg)
Milk co-products					
Cream	0.98	0.25	0.4	0.25	0.4
Skimmed milk used in the system to produce concentrated milk	0.33[a]	1.07	0.706	1.18	0.649
Skimmed milk exported from the system	0.33[a]	1.18	2.89	1.32	2.95
Egg co-products[b]					
Egg yolk	2.28	–	0.014	–	0.014
Egg white (not used in the system)	1.63				

[a] Based on average 2015 wholesale milk price plus profit of 35% (DairyCo, 2015).
[b] Amounts per kg of egg: egg yolk: 0.31 kg, egg white: 0.58 kg, egg shells: 0.11 kg. Original prices in USD sourced from Alibaba (2015), converted to British Pounds using the exchange rate of 1 USD = 0.652 GBP (year 2015).

eutrophication, marine eutrophication, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial acidification, agricultural land occupation, urban land occupation, natural land transformation, photochemical oxidant formation and mineral depletion.

In addition to these impact categories, primary energy demand (PED), volumetric water consumption (WC) and water footprint (WF) have also been estimated. The volumetric water consumption includes blue and green water and follows the approach developed by Hoekstra et al. (2011), accompanied by data from the Water Footprint Network (2016). The WF estimation is based on Pfister et al. (2009), accounting only for blue water abstraction and taking into account water stress in different regions. The WF has been estimated using the CCaLC (2015) software and database.

3. Results and discussion

This section presents first the environmental impacts of the different types of ice cream at the level of individual products, discussing different impacts in turn. This is followed by extensive sensitivity and uncertainty analyses. An evaluation of the impacts at the sectoral level, taking into account annual consumption of ice cream in the UK, is provided in section 3.2. Finally, different improvement opportunities, identified though a hotspot analysis, are discussed in section 3.3.

3.1. Environmental impacts at the product level

The results of the assessment are shown in Fig. 2, which shows that most of the impacts of the four types of ice cream differ by less than 10%. Global warming potential, for instance, ranges from 3.66 kg CO_2 eq./kg for chocolate regular to 3.94 kg CO_2 eq./kg for chocolate premium (excluding land use change). Chocolate regular ice cream is the best option for nine impacts, although only marginally better than the second best alternative, vanilla regular. The latter has slightly lower impacts than chocolate regular for five categories while their impacts are equal for the remaining four.

The greatest variation is found for freshwater and marine ecotoxicity, agricultural land occupation, mineral depletion, water consumption and water footprint. Consequently these are

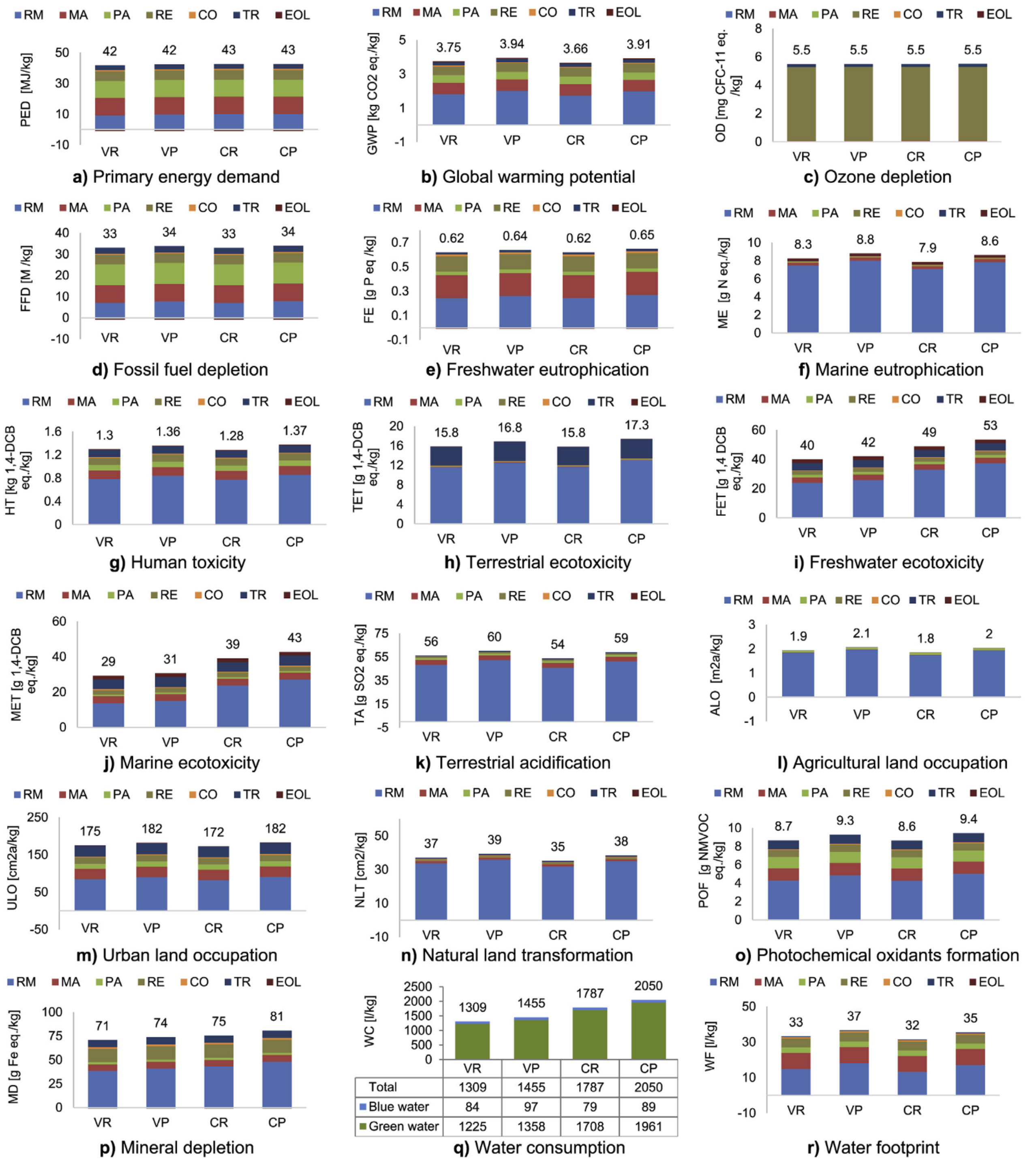

Fig. 2. Life cycle impacts of ice cream and the contribution of different life cycle stages. [VR: vanilla regular; VP: vanilla premium; CR: chocolate regular; CP: chocolate premium. RM: raw materials; MA: manufacturing; PA: packaging; RE: retailer; CO: consumption; TR: transport; EOL: end of life waste management].

discussed in turn below, followed by an overview of the remaining categories.

The main contributors to most impacts are the raw materials (ingredients), with only a few exceptions, as also discussed below. A detailed contribution analysis for all 18 categories can be found in Table S1 in the Supporting Information (SI).

Freshwater ecotoxicity (FET): The FET is estimated at 40–53 g 1,4-dichlorobenzene (DB) eq./kg, with vanilla regular ice cream having the lowest and chocolate premium the highest impact, respectively (Fig. 2i). Raw materials contribute more than 60% to the total, with raw milk production being the most significant contributor (35%–48%). This is mostly due to emissions from the concentrate used as cow feed. Cocoa powder is important in the chocolate versions (21%) whereas sugar makes a notable contribution (14%–16%) to all product types.

Marine ecotoxicity (MET): The highest marine ecotoxicity, as seen in Fig. 2j, is estimated at 43 g 1,4-DB eq./kg for the chocolate premium ice cream, falling to 29 g for vanilla regular. There is a clear distinction between the chocolate versions and their vanilla counterparts, with the former creating 34%–42% higher impacts as a result of pesticide and fertiliser usage during cocoa production. The contribution of raw materials ranges between 48% and 63%, with the majority attributable to raw milk and cocoa powder, which together account for approximately half of the total impact. Transport is also a notable contributor, causing 13%–19% of the MET.

Agricultural land occupation (ALO): This impact ranges between 1.8 and 2.1 m^2a/kg (Fig. 2l). The premium versions have 16% higher impacts than their regular counterparts. The raw materials stage causes the vast majority (94%–97%), largely due to the raw milk production. This explains the difference between the premium and regular products, as the former contain more cream and, therefore, require more agricultural land for milk production.

Mineral depletion (MD): As can be seen in Fig. 2p, the raw materials account for more than the half of this impact (54%–59%) while retail, manufacturing and transport together contribute at least 37%. Raw milk (44%–51%) and cocoa powder (10%) are the hotspots in the raw material stage. The freezer storage at the retailer (14%–16%) and the manufacturing are also influential, although their impact is seven times lower than that of the raw materials.

Water consumption (WC): In line with Hoekstra et al. (2011), water consumption is disaggregated into blue and green water and is depicted in Fig. 2q. The highest water consumption is associated with the chocolate premium ice cream, requiring 2050 l/kg, followed by the regular chocolate version (1787 l/kg). By comparison, premium vanilla requires 1455 l/kg and vanilla regular 1309 l/kg. The vast majority of the total (98%) is due to green water consumption, resulting from the cultivation of raw materials. Approximately half (42%–52%) of the blue water consumption also occurs in the raw materials stage, followed by manufacturing (23%–28%) and retail (13%–15%).

Water footprint (WF): The water footprints of the four ice creams range from 32 to 37 l/kg, with the highest value attributable to vanilla premium (Fig. 2r). Raw materials production is the main hotspot (41%–49%), followed by manufacturing (24%–27%). The impacts of the latter are primarily associated with the water needed to generate the electricity used in the manufacturing processes, followed by direct water consumption in cleaning operations. Retail is the third most contributing stage (14%–16%) with its impact dominated by electricity consumption. Finally, packaging contributes 8%–10%.

Other impact categories: The remaining 12 impact categories show little variation across the four ice cream product types, as can be seen in Fig. 2. Raw materials are the major hotspot for the majority of impacts, contributing more than 75% of the total to marine eutrophication, natural land transformation, terrestrial ecotoxicity and terrestrial acidification. The raw materials stage is also the main contributor (42%–63%) to global warming potential, freshwater eutrophication, human toxicity, urban land occupation, and photochemical oxidant formation. Throughout these categories, raw milk production is the main hotspot.

Only three impacts are not dominated by the raw materials. For ozone depletion, refrigeration at the retailer is the main contributor (95%) due to the production and leakage of refrigerants. For primary energy demand and fossil duel depletion, energy consumption in manufacturing (25%) and primary packaging (26%–30%) are key contributors owing to their upstream fossil fuel demand. Further details on the contribution of different life cycle stages and activities can be found in Tables S1 and S2 in the SI.

3.1.1. Comparison of results with literature

As discussed in the introduction, there is a general lack of LCA studies of ice cream both in the UK and globally, with the existing studies focusing on GWP. It can be seen from Fig. 2b that the estimate by the Scottish Government (2011) of 4 kg CO_2 eq./kg agrees quite closely with the present study's values of 3.66–3.94 kg CO_2 eq./kg. The Ben & Jerry's figure of 3.36 CO_2 eq./kg for a plain ice cream (Ben and Jerry, 2016) is also within this range. The only study which is out of range is that by Foster et al. (2006) with 0.97 kg CO_2 eq./kg. As mentioned earlier, this is due to the exclusion of the retail, consumption and waste management stages.

Owing to this lack of extensive LCA studies of ice cream, the following sections present the outcomes of the sensitivity and uncertainty analyses carried out to test the robustness of the impacts estimated in this work.

3.1.2. Sensitivity analysis

The following parameters could be expected to influence the results and are thus considered within the sensitivity analysis: land use change (LUC), allocation method, type of primary packaging, duration of frozen storage at manufacturers and retailer, and refrigerant type. Although the raw materials are a hotspot, they are not considered in the sensitivity analysis as changing product recipes affects the quality of the product.

To streamline the discussion, the analysis is focused on the vanilla regular option as similar trends can be expected for the other types. The only exception is the LUC where all four products are considered.

Land use change: The base-case GWP discussed in the previous section does not include land use change due to the uncertainty on whether and what kind of LUC is involved. For the purposes of the sensitivity analysis, it has been assumed that a rainforest is cleared and replaced by a perennial plantation for both cocoa and vanilla beans cultivation.

The results in Fig. 3 demonstrate that LUC associated with vanilla cultivation does not affect significantly the GWP of vanilla ice creams, increasing only by 4%–5%. However, the effect of LUC is much more significant for the chocolate ice creams, with their GWP increasing by 73%–75% due to cocoa cultivation. This is despite the low content of cocoa powder in the ice cream (3%–3.5% by mass). However, the GWP of cocoa powder with LUC (91 kg CO_2 eq./kg), sourced from DEFRA (2009), is highly uncertain according to DEFRA's own acknowledgement. Therefore, this estimated impact increase should be interpreted with caution.

Mass allocation: As discussed earlier, economic allocation has been used in the base case for milk and egg co-products. As the contribution of eggs to the impacts is very small, it is not considered in the sensitivity analysis and instead the focus is on milk which is one of the key contributors to the impacts.

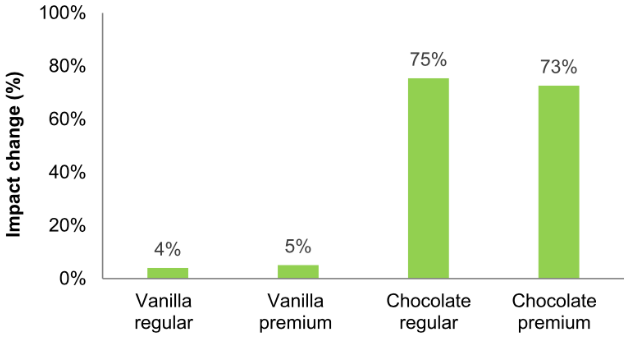

Fig. 3. The effect of land use change on global warming potential of ice cream.

If mass allocation is applied between milk and cream instead of the economic basis, the following impacts are most affected (Fig. 4): agricultural land occupation and natural land transformation decrease by 13%, marine eutrophication and terrestrial acidification by 12%, terrestrial ecotoxicity by 10%, and global warming potential, human toxicity and mineral depletion by 8%. The other impacts are not affected.

Primary packaging: Polypropylene (PP) ice cream tub is a notable hotspot for fossil fuel depletion and primary energy demand, contributing 22% and 19% to the total, respectively. High-density polyethylene (HDPE) is also used extensively in manufacturing and in the food sector in general. Hence, it could be used instead of PP, particularly as both materials have similar densities (Plastics Europe, 2015).

The results suggest that replacing PP by HDPE affects only four impact categories, reducing them by less than 10% (Fig. 5): primary energy demand, global warming potential, fossil fuel depletion and human toxicity. Thus, the primary packaging material has limited influence on the results. The same conclusion applies to the other three ice cream types since the packaging is independent of ice cream composition.

Storage time at manufacturer: The energy consumed for deep freezing is the main contributor to the impacts from ice cream manufacturing. Therefore, the influence of the storage period is considered as part of this sensitivity analysis. Two further storage times are included in addition to the baseline of 30 days: 15 and 60 days. Only six impacts are affected by this change (Fig. 6). Doubling the storage period to 60 days increases the impacts of vanilla regular ice cream by 6%–13% while halving it to 15 days, decreases them by up to 5%. Since the storage time does not depend on the composition of ice cream, similar variations occur for the other three types of product examined in this work.

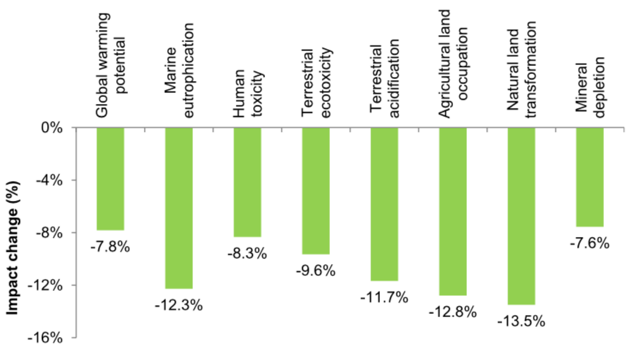

Fig. 4. The effect of mass allocation on the impacts of vanilla regular ice cream relative to economic allocation.

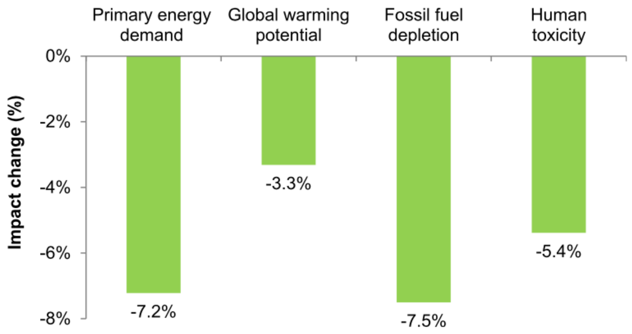

Fig. 5. The effect on the impacts of vanilla regular ice cream if polypropylene primary packaging is replaced by high-density polyethylene.

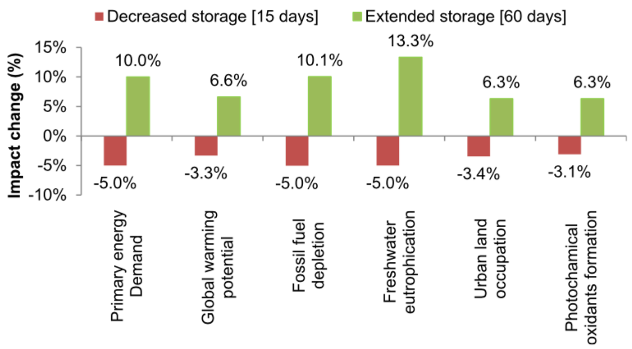

Fig. 6. The effect of storage time at manufacture on the impacts of vanilla regular ice cream relative to the base case (30 days).

Storage time at retailer: Refrigeration at the retailer is the key hotspot for ozone depletion, contributing to 90% to the total impact. It also accounts for 10% of the total primary energy demand, fossil fuel depletion, global warming potential and freshwater eutrophication. Thus, both reduced (3 days) and extended (14 days) storage periods are considered to examine the effect on the impacts in comparison to the storage duration in the base-case (one week).

As indicated in Fig. 7, changing the storage time leads to significant changes in 10 impacts (the others are not affected). For the extended storage of 14 days, ozone depletion increases by 95%, primarily due to refrigerant leakage. Moreover, freshwater eutrophication increases by 22% and mineral depletion by 19%, also due to the leakage. On the contrary, if the storage time is reduced to 3 days, ozone depletion is reduced by more than half (54%) and freshwater eutrophication and mineral depletion by 12%. The other seven impacts are also slightly lower (4%–6%). Similar changes apply to the other three product types.

Refrigerant type: In addition to the storage time, the type of refrigerant also affects ozone depletion. To explore this effect at the retail stage, the impact of R134a is compared to R22, R152a and ammonia. As the latter is already used in the manufacturing process, its replacement is not considered within the sensitivity analysis as it does not contribute much to the impacts.

As can be seen in Fig. 8, using R22 would reduce ozone depletion by 74%, while using R152a or ammonia would decrease it by up to 95%. R22 would increase the GWP only very marginally (by 0.3%) and R152a would reduce it by 1.1%. The effect on the other impact categories is negligible.

3.1.3. *Uncertainty analysis*

The uncertainty analysis has been carried out by varying

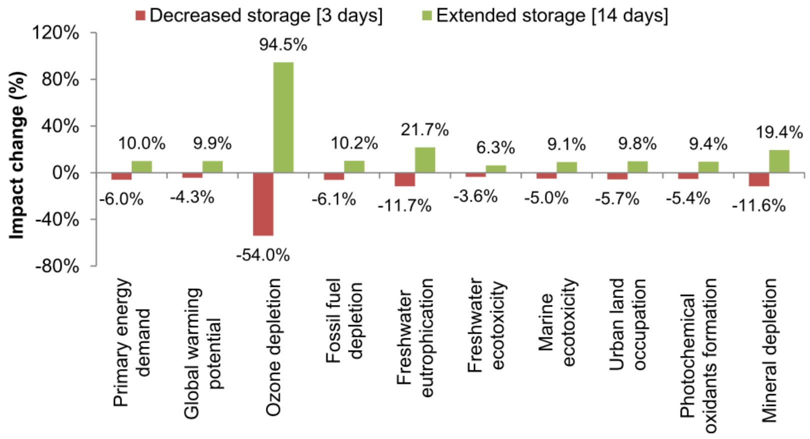

Fig. 7. The effect of storage time at retailer on the impacts of vanilla regular ice cream relative to the base case (one week).

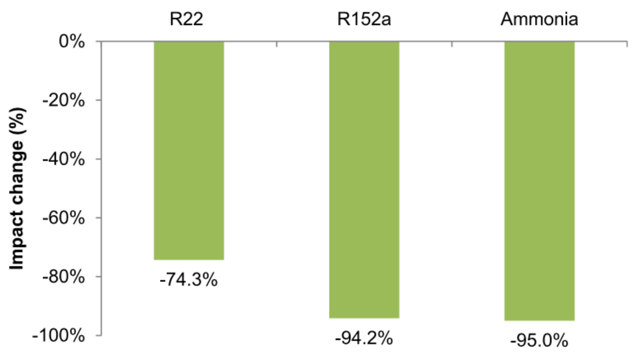

Fig. 8. The effect of type of refrigerant used at retailer on ozone depletion of vanilla regular ice cream relative to the base-case refrigerant (R134a).

simultaneously a range of input parameter values, focusing on parameters that are independent of each other. Stochastic modelling has been applied, using Monte Carlo simulation to vary parameter values randomly through 20,000 iterations. In the absence of other information, all parameters are assumed to vary following a uniform distribution. Moreover, LUC is included in the simulation to ensure that it captures the maximum possible impacts. Gabi V6.4 (Thinkstep AG, 2016) has been used to perform the Monte Carlo simulations.

The parameters investigated are storage time at the manufacturer and at the retailer, with ranges of 15–60 days and 3–14 days, respectively. These parameters are selected because of their uncertain values and strong effect on the results, as shown in the sensitivity analysis. The results of the uncertainty analysis are depicted in Fig. 9 for all four types of ice cream for the four most affected impacts. The remaining impacts show less variation and are not shown. Detailed statistical data arising from the uncertainty analysis can be found in Table S3 in the SI.

As can be seen in Fig. 9, the variations in the impacts from the mean values obtained in the uncertainty simulations are relatively small across the product types. The only exception is ozone depletion, which ranges from −33% to +150% relative to the mean value. This indicates once again the significance of frozen-storage time for this impact.

It can also be observed in Fig. 9 that the impacts of the four ice cream products often overlap when taking into account their ranges. In such cases, a comparison indicator (CI) can be used to estimate the probability that the impact of one product is higher than the impact of another (Huijbregts, 1998). For instance, the uncertainty analysis has revealed significant GWP deviations between the vanilla and chocolate ice creams but overlapping ranges for the regular and premium versions of each flavour (Fig. 9). Hence, to estimate the probability of the GWP of a premium version being higher than the respective regular, the CI has been calculated using @RISK 7 in Microsoft Excel. The results of a Monte Carlo simulation with 20,000 iterations are shown in Fig. 10. The assessment assumes triangular distributions for the individual GWP due to the relatively high probability of each product lying near the average impact value.

As can be inferred from Fig. 10a, the probability of vanilla premium ice cream having a higher GWP than vanilla regular is 68.4% (estimated by integrating the area delineated by the vertical line and the relative frequency curve on the right). For the chocolate ice creams, there is a probability of nearly 92% that the premium version has a higher GWP than its regular equivalent (Fig. 10b). Consequently, premium ice creams are very likely to have higher GWP than regular ones.

This analysis is less relevant for the other impacts as the ratios between the products are very small.

3.2. Environmental impacts at the sectoral level

This section presents the annual impacts of ice cream at the sectoral level. These have been estimated using the results at the product level discussed in section 3.1 and the amounts of ice cream sold annually in the UK. Data on specific product sales are not available in the public domain. Instead, they have been determined in this study using the market share of the different product categories (Key Note, 2015) and their prices at leading retailers. The total amount of all ice cream products sold annually is estimated at 404,274 t, with the following breakdown:

- vanilla and chocolate regular: 27,500 t each;
- vanilla and chocolate premium: 44,300 t each; and
- other ice cream products: 260,674 t.

For the estimates, see Table S4 in the SI. Based on these figures, it can be observed that the flavours considered in this work occupy nearly 36% of the market, with an assumed equal share each. As this is the first study to consider a full LCA of ice creams, estimates of the impacts of other products are not available. Therefore, to approximate these, a conservative approach is adopted whereby each of their impacts is assumed to be equal to the highest impact of the

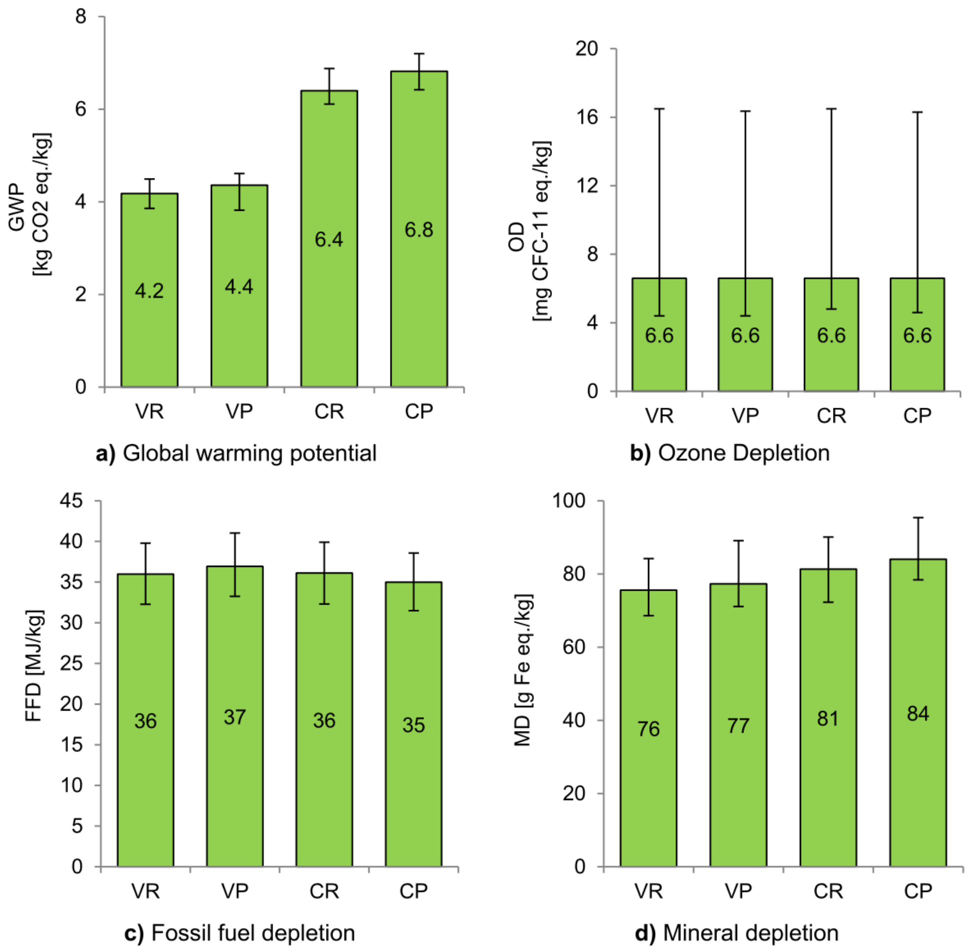

Fig. 9. Results of the uncertainty analysis for the four types of ice cream. [VR: vanilla regular; VP: vanilla premium; CR: chocolate regular; CP: chocolate premium.].

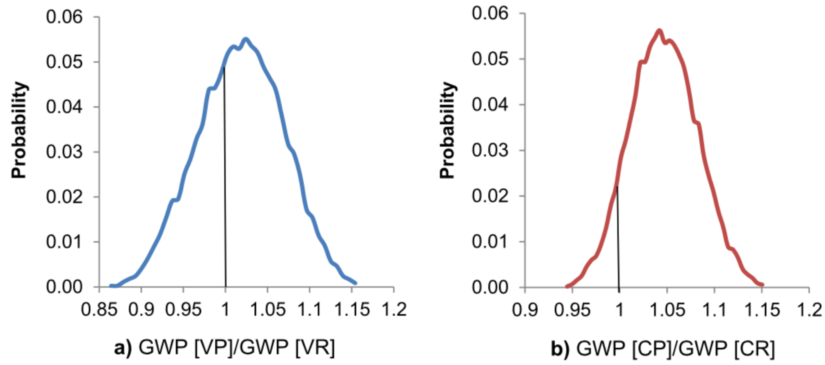

Fig. 10. Probability distribution of the comparison indicator for global warming potential (GWP). [VR: vanilla regular; VP: vanilla premium; CR: chocolate regular; CP: chocolate premium.].

other four flavours for that category.

The results are summarised in Fig. 11. For example, the annual GWP is estimated at 1.57 Mt and primary energy demand at 17,300 TJ. The latter represents 3.8% of the total energy consumed in the food and drink sector, based on the DEFRA (2006b) estimate of 126 TWh/yr. However, the DEFRA estimate for the sector only considers energy used in production processes, excluding the rest of the life cycle. Thus, the life cycle energy consumption of the whole food and drink sector is higher than 126 TWh/yr, and consequently the overall ice cream's contribution is probably much less than 3.8%. The contribution to the greenhouse gas (GHG) emissions is even lower, estimated at 1.8%. This value is based on

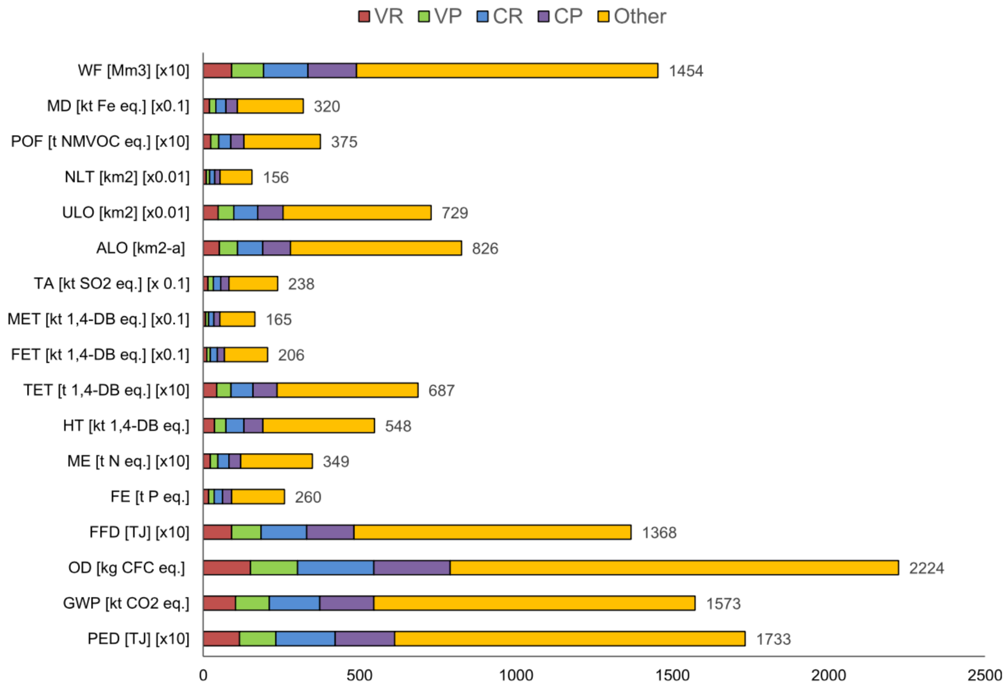

Fig. 11. Annual environmental impacts from ice cream consumption in the UK. [VR: vanilla regular; VP: vanilla premium; CR: chocolate regular; CP: chocolate premium. For the impacts nomenclature, see Fig. 2. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor in brackets for relevant impacts.].

the total UK emissions of 550 Mt CO_2 eq./yr, taking into account a consumption perspective and the contribution of the food and drink sector to the total UK emissions of 15% (Druckman and Jackson, 2009). It is not possible to put the other impacts into context since no sectoral or national data exist.

It can also be seen in Fig. 11 that the 'other ice cream' products contribute around 2/3^{rds} of the impact, in line with their market share. However, these results should be interpreted with caution due to the conservative assumptions on the impacts of the other products. Nevertheless, they provide at least an order of magnitude of the potential impacts from the ice-cream sector and as such can be used to identify opportunities for improvements. These are discussed in the next section.

3.3. Improvement opportunities

Based on the results of this study, the main focus in terms of reducing the impacts should be the raw materials stage, especially raw milk production and cocoa cultivation. The impacts of milk could be reduced by modifications of animal feed (Roibas et al., 2016) and by composting the manure instead of leaving it on land (Hogaas, 2002). Based on these prior works, investigations undertaken within the present study have revealed that a 50% replacement of dried by fresh grass in combination with manure composting could reduce GWP by 16%, eutrophication by 8% and acidification by 9%. The other impacts are not affected. The impacts could also be reduced by reducing the amount of cream (and therefore the milk) in the recipe, but that could affect the quality of the products and most manufacturers would not consider that option.

However, new manufacturers are starting on emerging, particularly in the UK and US, that have taken a more radical approach to ice cream formulation to produce low fat and sugar products. This change has been driven by health concerns related to a high intake of these ingredients with processed food. Examples of such manufacturers include Oppo in the UK and Halo Top in the US, whose products are taking these two markets by storm, challenging established ice cream manufacturers and their products. Therefore, product reformulation is possible, but is still seen as risky by mainstream producers and will probably take time to spread more widely.

The results also show that cocoa powder causes significant ecotoxicity impacts. Ntiamoah and Afrane (2008) suggest that this could be addressed by reducing the use of conventional fertiliser and/or replacing them by organic alternatives as well as reducing the amount of pesticides applied. However, these measures will also lead to lower yields, which will ultimately increase the overall impacts from cocoa production. Further consideration of these aspects is outside the scope of this study but could be a focus of future work.

In the manufacturing stage, less energy-intensive processes should be considered, in combination with energy optimisation and a switch to low-carbon energy sources. However, due to the dominance of raw materials for most of the impacts, energy savings of more than 25% in manufacturing are required to trigger noteworthy impact mitigations. For instance, such a change would decrease primary energy demand by 7%, fossil fuel depletion by 6% and freshwater eutrophication by 8%. If the energy reduction can be combined with a decrease in the storage time from 30 to 15 days, then the primary energy demand would be reduced by 12%, fossil fuel depletion by 11% and freshwater eutrophication by 14%.

Finally, reducing the storage time and using environmentally benign refrigerants would lower ozone depletion significantly, as demonstrated in the sensitivity analysis.

4. Conclusions and recommendations

This paper has evaluated the environmental sustainability of ice cream by considering the whole life cycle of four market-leading types of ice cream: premium and regular variants of both chocolate- and vanilla-flavoured products. The life cycle assessment results suggest that the impacts of the four products are broadly similar across a range of 18 impact categories, with chocolate regular being a slightly better option for the majority of impact categories. The exceptions to this trend are freshwater and marine ecotoxicity, agricultural land occupation, mineral depletion, water consumption and water footprint. In these categories, the ice creams show variance of at least ±10% between products, with chocolate products on average having a higher impact than vanilla by approximately 16%.

Another notable trend in the results is that the premium versions of ice cream have higher environmental impacts than the regular ones. For instance, the uncertainty analysis suggests that the probability of premium versions having a higher global warming potential than the regular is around 68% for vanilla ice cream and 92% for chocolate.

The raw materials contribute most to all impacts categories, except for fossil fuel depletion where manufacturing dominates. Within the raw materials stage, raw milk causes the vast majority of the impacts. Furthermore, cocoa powder can add significantly (70%) to the global warming potential if land use change is involved.

Manufacturing impacts are mostly attributable to the energy consumption, particularly due to the hardening process and deep freezing. Retail is the most significant contributor to ozone depletion, accounting for approximately 95% of the total impact. This is mainly due to the production and leakage of refrigerants.

The impacts are sensitive to the duration of ice cream storage at the manufacturer and retailer as well as the type of refrigerant used. Using mass instead of economic allocation and replacing polypropylene with high density polyethylene packaging have a moderate effect on the impacts.

Based on the annual UK consumption of ice cream of 404 kt, it is estimated that the sector consumes around 17 TJ of primary energy per year and emits 1.5 Mt CO_2 eq. The latter represents 1.8% of the GHG emissions from the whole food and drink sector in the UK.

Future improvements in the sector should focus on milk and cocoa production and possibly on changing product formulation to reduce the amount of these two ingredients. Reducing storage time is another key improvement option as is the use of refrigerants with low ozone depletion and global warming potentials. It is expected that the results of this work will be of interest to manufacturers, policy makers and consumers, helping them make informed environmentally-driven decisions related to ice cream.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.10.237.

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