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DOI:
10.1016/j.foodres.2018.02.042

Document Version
Accepted author manuscript

Link to publication record in Manchester Research Explorer

Citation for published version (APA):
Konstantas, A., Jeswani, H., Stamford, L., & Azapagic, A. (2018). Environmental impacts of chocolate production and consumption in the UK. *Food Research International*. https://doi.org/10.1016/j.foodres.2018.02.042

Published in:
Food Research International

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Download date:25. Apr. 2024

Food Research International, 2018, https://doi.org/10.1016/j.foodres.2018.02.042

Environmental impacts of chocolate production and consumption in the UK

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Abstract

This study evaluates life cycle environmental impacts associated with chocolate products made and consumed in the UK. The paper focuses on three representative chocolate products occupying 90% of the market: 'moulded chocolate', 'chocolate countlines' and 'chocolates in bag'. The impacts were estimated using life cycle assessment (LCA) as a tool and following the ReCiPe impact assessment method. The water footprint was also considered. For example, the global warming potential ranges between 2.91–4.15 kg CO_2 eq., primary energy demand from 30–41 MJ and the water footprint, including water stress, from 31–63 l per kilogram of chocolate. The raw materials are the major hotspot across all impact categories for all three product types, followed by the chocolate production process and packaging. The raw material impacts are mainly due to milk powder, cocoa derivatives, sugar and palm oil. The sensitivity analysis shows that the results for global warming potential are sensitive to land-use change (LUC) associated with cocoa production, increasing the impact of the chocolate products by three to four times if LUC is involved. The improvement opportunities targeting the key contributing stages suggest that GWP of chocolates could be reduced by 14%-19%. Chocolate countlines have the highest contribution to the total impacts at the UK level (37%–43%), followed by chocolates in bag (28%–33%). Moulded chocolates and other chocolate confectionary make up the rest of the impacts, with a roughly equal share each. Chocolate consumption in the UK contributes 4.7% to the primary energy consumption and 2.4% to the GHG emissions from the whole food and drink sector. The results of this work will be of interest to policy makers, chocolate producers and consumers, helping them to make more informed decisions towards sustainable production and consumption of chocolate products.

Keywords: Chocolate; climate change; environmental sustainability; life cycle assessment; food supply chains

1 Introduction

Chocolate products are the most widespread desserts and snacks around the globe (ICCO, 2016). They are made from cocoa beans obtained from the tree *Theobroma cacao,* an indigenous tree to South America (Afoakwa, 2016). Cocoa was firstly cultivated by the Aztecs while the Spanish were the first to bring its beverage to Europe in the 15th century (Afoakwa, 2016). At that time, chocolate was very expensive and its consumption was reserved for the wealthier social classes in Europe. Later on, with addition of milk and sugar as well as due to the breakup of the cocoa monopoly, chocolate became more popular (Beckett, 2009). The use of cocoa to produce diverse and industrialised products began in the UK in the 19th century where the first plain chocolate bars were produced (Beckett, 2009).

Cocoa is mainly cultivated around the equator in humid climate conditions. Cote D'Ivoire, Ghana, Indonesia, Nigeria, Ecuador and Brazil are the major producers and exporters of cocoa beans (ICCO, 2016). According to ICCO (2016), the annual production of cocoa beans in 2016 was 4.25 million tonnes. The worldwide sales of chocolate were estimated to be worth more than US$101 billion in 2015 (Statista, 2015) with Europe accounting for 45% of the global consumption (Afoakwa, 2016). Chocolate products are also very popular in the UK – with an estimated consumption of 7.9 kg/person (Afoakwa, 2016), the country ranks the sixth highest chocolate-consuming country in the world (Caobisco, 2015).

The UK chocolate confectionary sector, which was worth £4.34 billion in 2014, grew by 16.4% and is expected to grow by a further 8.8% by 2019 (Key Note, 2015). The sector is divided into four categories: i) chocolate countlines; ii) sharing bags and boxed chocolates ('chocolates in bag'); iii)

blocks and moulded bars ('moulded chocolates'); and iv) other chocolate confectionary goods. The first three categories account for more than 90% of the total sales volume, most of which are milk-based products as dark chocolate is not very popular in the UK. As shown in Fig. 1, chocolate countlines dominate the market with the share of 41.8%, followed by chocolates in bag (30%) and moulded chocolates (19.5%). The remaining 8.7% are other chocolate confectionary products which include seasonal products, such as those sold during Christmas and Easter, and various "novelty" products (Key Note, 2015).

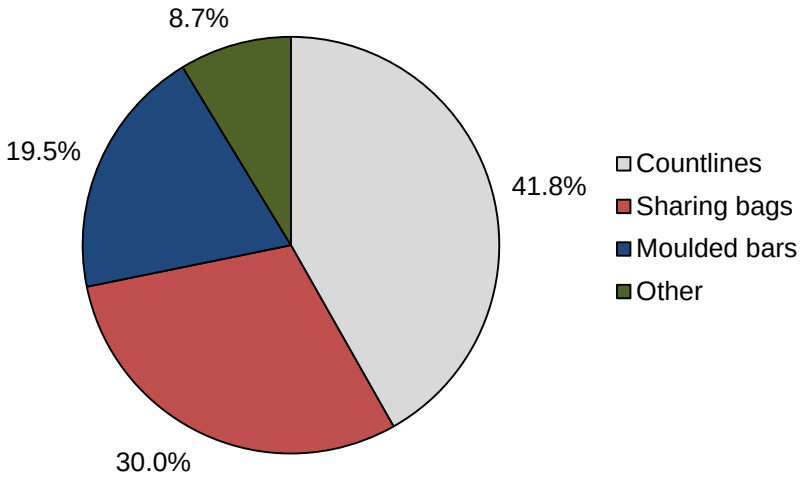


Fig. 1. Breakdown of the chocolate confectionary sector in the UK by market value (Key Note, 2015)

So far, there have been few other studies of environmental impacts of chocolates. Most of these focused on dark chocolate, with two studies based in Italy (Recanati et al., 2018; Vesce et al., 2016), one in Ecuador (Perez Neira, 2016) and one in Europe in general (Busser & Jungbluth, 2009). The last also considered milk chocolate in aluminium packaging. All the studies followed the life cycle of chocolate from cradle to grave, apart from that by Vesce et al. (2016) which was a gate-to-gate study. Unlike the previous studies which concentrated on individual chocolate products, this paper considers a range of chocolate confectionary products to evaluate environmental impacts of chocolate production and consumption in the UK. The next section provides details on the product categories considered and gives an overview of the methodology used to evaluate the environmental impacts.

2 Methodology

Life cycle assessment (LCA) was used to estimate the impacts of chocolate products, following the ISO 14040/14044 guidelines (ISO, 2006a&b). The methodology, data and the assumptions are described in more detail in the following sections.

2.1 Goal and scope

The goal of the study is to assess the environmental impacts of production and consumption of chocolate products in the UK. The study considers the following market-leading products in each of the three main sub-sectors (Mintel, 2015): chocolate coated wafers (chocolate countlines), milk chocolate (moulded chocolate) and malty chocolates (chocolates in bag). The impacts are first assessed at the product level with the functional unit defined as '1 kg of packaged chocolate consumed at home'. The second part of the study considers the annual impacts of chocolate consumption in the UK for which the functional unit is the 'annual consumption of chocolates in the UK'.

As outlined in Fig. 2, the system boundary is from cradle to grave, comprising the following stages:

- Raw materials (ingredients): production of sugar, milk powder, cocoa butter, vegetable fat, cocoa mass, flour, pasteurised eggs, salt, butter, whey powder and starch.
- Manufacturing: electricity, steam and water consumption in the manufacturing processes, including cleaning activities.
- Packaging: aluminium foil (primary), corrugated-boxes and stretch film (secondary and tertiary).
- Distribution and consumption: storage in a regional distribution centre and at retailer, and consumption at home.
- Waste management: treatment and disposal of process and post-consumer waste.
- Transport: transport of raw materials and packaging to the production facility, product and waste transport along the life cycle.

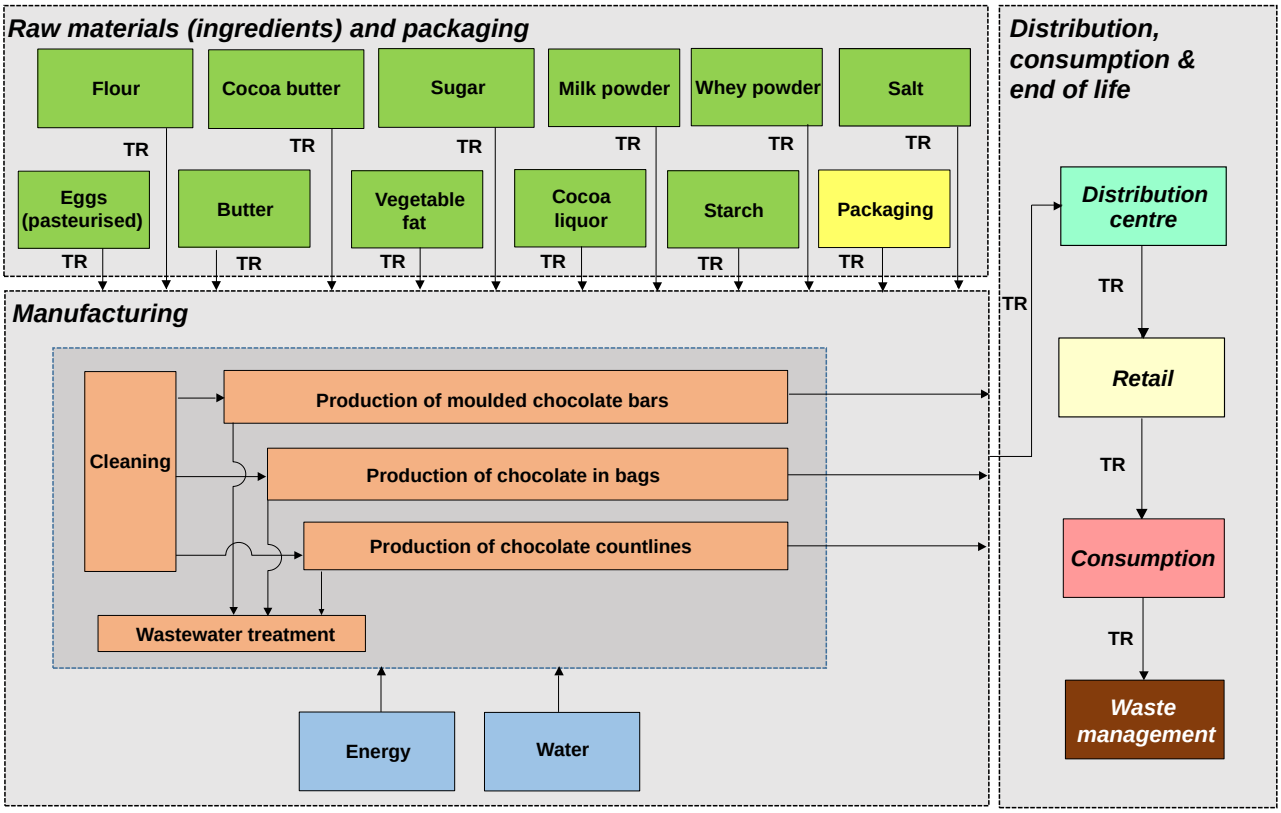


Fig. 2. Life cycle stages of chocolate products considered in the study
[TR: transport]

2.2 Inventory data and assumptions

The foreground data were sourced from publically available information provided by manufacturers and from the literature. The background life cycle inventory (LCI) data were obtained from Ecoinvent V2.2 (Ecoinvent, 2010). Any data gaps were filled using Ecoinvent V3.3 (Ecoinvent, 2016) and the GaBi database (Thinkstep AG, 2016) as detailed further below.

2.2.1 Raw materials (ingredients)

The main ingredients for all chocolate types are sugar, milk powder, cocoa butter and cocoa liquor; however, their composition varies among the considered products as shown in Table 1. The data sources and key assumptions for these ingredients are described below.

Milk powder is produced from UK raw milk. The milk production was modelled using data from the Scottish Government (2011) study. The data on energy consumption for milk processing and milk powder production were obtained from Brush et al. (2011). The cleaning activities in the milk-powder manufacturing facility were modelled according to DeJong (2013) and Hogaas (2002), while wastewater quantities and its onsite treatment are based on data from Envirochemie (2016) and Ecoinvent (2010), respectively.

Table 1 Ingredients of chocolate products (Beckett, 2009).

Ingredient	Milk chocolate (%)	Chocolate countlines[a] (%)	Chocolates in bag[b] (%)
Sugar			
in milk chocolate	45	29.70	32.85
in wafers		8.33	
in white chocolate			4.81
in malted milk powder			4.66
Milk powder			
in milk chocolate	24.5	16.17	17.89
in white chocolate			4.29
in malted milk powder			4.66
Cocoa butter			
in milk chocolate	17	11.22	12.41
in white chocolate			3.90
Vegetable fat	5	3.30	3.65
Cocoa liquor	8	5.28	5.84
Emulsifiers[c]	0.5	0.33	0.37
Flour			
in wafers		11.56	
in malted milk powder			2.34
Eggs (pasteurised)		0.24	
Salt		0.07	
Water		13.33	
Butter		0.24	
Whey powder		0.24	
Starch			2.34

[a] Chocolate enrobing makes up 66% of the total plain-product weight and the rest is the wafer.
[b] According to manufacturers' specification, 73% is milk chocolate and the rest is divided equally between white chocolate and malted milk powder.
[c] Emulsifiers are excluded from the study as data were not available for their environmental impacts.

The production of milk butter and whey powder is based on Ecoinvent V3.3 data while the evaporation process was modelled based on Westergaard (2010). The LCI data for these two ingredients were sourced from Ecoinvent V3.3 as they were not available in Ecoinvent V2.2. However, the raw milk production and the energy mix were modified to correspond to the UK conditions by replacing the corresponding data in the Ecoinvent V3.3 inventory.

Cocoa butter and cocoa liquor are produced in the UK from cocoa beans cultivated in West Africa. The environmental profiles of these cocoa products are based on Ntiamoah and Afrane (2008) as adopted in the product environmental footprint (PEF) data in EC (2015a). The land-use change was not considered in the base case but its effect on the impacts was explored through a sensitivity analysis. Economic allocation was used for the cocoa co-products based on their market prices; the influence of mass allocation was also considered in the sensitivity analysis.

Wheat is cultivated in the UK and milled to produce flour, the main ingredient for manufacturing malted milk powder. The milling process was modelled using data from EC (2015b), Manley (2000) and Ecoinvent (2010), while wheat LCI data were obtained from the AgriLCA model (Audsley et al., 2009), Ecoinvent (2010) and the Agri-footprint database (Blonk, 2015). Economic allocation was used for allocating the impacts between the flour and the bran.

Barley was assumed to be the main ingredient for producing starch. Starch was modelled using data from EC (2015c), Ecoinvent (2010) and the AgriLCA model (Cranfield University, 2005) for barley cultivation in the UK.

Pasteurised eggs were modelled using egg production data from the PROBAS database (UBA, 2016) and pasteurisation process according to EC (2015b). It was assumed that 40% of sugar is produced from locally cultivated sugar beet and the rest from the imported sugar cane. Sugar was modelled using Ecoinvent (2010) data. Palm oil was assumed to be the main source for the

vegetable fat and the LCI data were obtained from the Ecoinvent (2010) and GaBi (Thinkstep AG, 2016) databases.

2.2.2 Manufacturing

This section describes the manufacturing processes for producing chocolates. The data on energy consumption across all individual processes are detailed in Table 2.

Table 2 Production processes and associated energy consumption.

Processes and activities	Natural gas (MJ per kg material processed)	Electricity (MJ per kg material processed)	Data sources
Mixing			
Ingredients for chocolate		0.0211	Hamburger & Dresdner (2016)
Ingredients for wafers		0.113	Brush et al. (2011)
Refining		0.132	Hamburger & Dresdner (2016)
Conching		0.13	Hamburger & Dresdner (2016)
Tempering		0.0135	Hamburger & Dresdner (2016)
Moulding		0.187	Brush et al. (2011)
Cooling		0.36	Brush et al. (2011)
Packing		0.364	Brush et al. (2011)
Cleaning			
For moulded chocolate bars		0.364	UBA (2016)
For chocolate countlines		0.63	UBA (2016)
For chocolates in bag		0.18	UBA (2016)
Shaping		0.303	Brush et al. (2011)
Baking	4.16		Brush et al. (2011)
Enrobing		0.28	Brush et al. (2011)
Panning		0.187	Hamburger & Dresdner (2016)

The production of milk chocolate involves mixing of ingredients, refining, conching, tempering and moulding (Beckett, 2009). Afterwards, the chocolate bars are cooled and packaged. A slightly different production method is followed for producing the chocolate countlines, which includes two separate production lines. The first encompasses producing wafers, which involves mixing of ingredients, shaping, baking and cooling processes (Manley, 2001). The second is identical to that used for producing milk chocolate. In the next step, wafers are enrobed with chocolate, cooled and packed. The manufacturing of the chocolates in bag involves the production of milk chocolate, white chocolate and malted milk powder. White chocolate is produced in the same way as milk chocolate, which is then panned with the malted milk powder. The panned mix is coated with milk chocolate, cooled and packed.

The energy use associated with the chocolate mixing, refining, conching, tempering and panning processes was obtained from the Hamburg & Dresdner machine factories (2016) while for the other production processes the data were obtained from Berkley Energy Laboratory (Brush et al., 2011). The energy for cleaning activities was calculated as 10% of the total facility demand (UBA, 2016).

2.2.3 Packaging

The chocolate products are packaged into aluminium foil (primary packaging), which are then packed into corrugated-board boxes (secondary packaging) that are wrapped in low density polyethylene (LDPE) film (tertiary packaging). The amount of the primary packaging materials used for the chocolate products was obtained by weighing the packaging for the representative products. The amount of secondary material was evaluated after weighing and allocating it to 1 kg of the respective product (the functional unit). Tertiary packaging materials were obtained from the literature (EC 2016a). Consumer plastic bags were also considered. The data for the packaging of the products are given in
Table 3.

Table 3 Inventory data for packaging.

Packaging	Milk chocolate (g/kg)	Chocolate countlines (g/kg)	Chocolates in bag (g/kg)
Aluminium foil (primary packaging)	15	25.3	39.8
Cardboard (secondary packaging)	68.4	56.6	137
LDPE[a] (tertiary packaging)	0.47	0.47	0.47
LDPE[a] (consumer plastic bags)	2.4	2.5	3.5

[a] Low density polyethylene

The production of the packaging materials was modelled using inventory data from Ecoinvent (2010) and EAA (2013). Aluminium foil is produced from an aluminium mix which was assumed to contain 32% secondary aluminium (Classen, et al., 2009). Corrugated-board was modelled according to data in Hirshier (2007) and assuming 78% recycled content. Finally, tertiary packaging and consumer plastic bags were modelled using Ecoinvent (2010) data assuming use of LDPE packaging film.

2.2.4 Distribution and retail

It was assumed that the products are stored for four weeks in distribution centres and two weeks in supermarkets at an ambient temperature. Electricity consumption for ambient storage and water use were estimated in accordance with EC (2016a).

2.2.5 Waste management

All relevant solid and liquid waste streams associated with the production processes, distribution and post-consumption stages were considered (Table 4). It was assumed that solid process waste, which includes 2% losses of ingredients, is composted and that wastewater is treated before discharge. The waste disposal routes for other waste streams were assumed as per the current waste management practices in the UK (EC, 2016b,c). In accordance with ISO 14044 (ISO, 2006b), the system was credited for energy recovery, composting and aluminium recycling.

Table 4 Inventory data for the process and post-consumer waste management activities

Type of waste and treatment	Milk chocolate (g/kg)	Chocolate countlines (g/kg)	Chocolates in bag (g/kg)	Sources of LCA data
Wastewater [a] (onsite treatment)	2700	2700	2700	Modelled using data from Ecoinvent (2010)
Process losses[b], composting	20	20	20	Ecoinvent (2010)
Corrugated cardboard[c]	68.4	56.6	137	86.5% recycling and 13.5% incineration with energy recovery (EC, 2016c)
Aluminium packaging[d]	15	25.3	39.8	Aluminium recycling rate: 41.8% (EC, 2016b); the rest is landfilled.
Plastic waste				58% landfill, 34% incineration with energy recovery and 8% incineration without energy recovery (EC, 2016b).
Tertiary packaging	0.47	0.47	0.47	
Plastic bags	2.4	2.5	3.5	

[a] Due to a lack of data on the amount of wastewater in the chocolate industry, the equivalent of a UK based confectionary manufacturer was used.
[b] Losses in the manufacturing processes were assumed at 2%.
[c] The efficiency of the corrugated-board recycling process is 90% (Ecoinvent, 2010).
[d] The efficiency of the aluminium recycling process is 96% (EAA, 2013).

2.2.6 Transport

Table 5 details transport distances and modes as well as the place of origin of the transported goods. Road distances were obtained from EC (2016a) in accordance with the Eurostat transport data while sea transport distances were estimated using the Searates (2016) route calculator. Where data were not available, assumptions were made in accordance with EC (2016a).

Table 5 Transportation means and distances

Life cycle stage	Transport step	Country of origin	Transportation means	Distance (km)
Raw materials	Sugar from sugar beet	UK	Lorry (16-32 t)	200 [a]
	Sugar 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
	Palm/ Palm kernel oil			
	by sea	Malaysia to UK	Freight ship	15,900
	by road	UK	Lorry (16-32 t)	200
	Cocoa beans			
	by road	Ghana	Lorry (16-32 t)	500[a]
	by sea	Ghana to UK	Freight ship	7370
	by road	UK	Freight ship	200
	All other ingredients	UK	Freight ship	200
Manufacturing	Manufacturer to distribution centre	UK	Lorry 16-32 t	150[a]
Distribution centre	Distribution centre to retailer	UK	Lorry 3.5-7.5 t	200
Packaging	Packaging to manufacturer	UK	Lorry (16-32 t)	200[d]
	Plastic bags to retailer	UK	Lorry (16-32 t)	200
Consumption	Retailer to consumer	UK	Car[a]	0.135[b]
End of life	Waste to recycling	UK	Lorry (7.5-16 t)	100
	Waste to landfill	UK	Lorry (21 t)	30[c]
	Waste to incineration	UK	Lorry (21 t)	30[c]

[a] Source: EC (2016a).
[b] Distance assigned to the functional unit considering 6.4 km roundtrip divided by 28 kg consumer basket and 59% of distance travelled by car (Pretty at al., 2005).
[c] Distance for transporting waste to landfill/incineration plant.

2.3 Impact assessment

GaBi V6.4 software (Thinkstep, 2016) was used to model the system and the ReCiPe midpoint method (Goedkoop et al., 2013) was applied to estimate the environmental impacts. The following impact categories were considered: Global warming potential (GWP), ozone depletion (OD), fossil fuel depletion (FFD), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), terrestrial acidification (TA), Agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), photochemical oxidant formation (POF) and mineral depletion (MD).

Furthermore, primary energy demand (PED), volumetric water consumption and water footprint were also estimated. PED was estimated using GaBi software. The volumetric water consumption was quantified taking into account blue and green water, following the approach developed by Hoekstra et al. (2011) and using data provided by the Water Footprint Network (2016). The water footprint was estimated following the approach by Pfister et al. (2009), taking into account water stress in different regions; this approach considers only blue water. The WF was estimated using CCaLC (2015) software and database.

3 Results and discussion

The results are presented in Fig. 3 and Tables S-1 and S-2 in the Supplementary information (SI) and are discussed for each impact in turn below.

3.1 Environmental impacts

Primary energy demand (PED): As shown in Fig. 3a, chocolates in bag have the highest PED, which is estimated at 40 MJ/kg while the other two products consume 30 MJ/kg. For all three products, the majority of the impacts are associated with the production of raw materials (49%–66%). Milk powder (31%– 47%) is the main contributor to PED used for the production of raw materials. Other activities that significantly contribute to energy consumption are the manufacturing processes and the primary packaging. For the chocolate countlines, manufacturing accounts for 26% of the total and for chocolates in bag, packaging contributes 21%.

Global warming potential (GWP): The GWP of the chocolate products shows a similar trend as the PED (Fig. 3b). Chocolates in bag have the highest impact (4.15 kg CO_2 eq./kg), followed by moulded chocolate (3.39 kg CO_2 eq./kg) and chocolate countlines (2.91 kg CO_2 eq./kg). The contribution analysis shows that production of the raw materials is the major hotspot, accounting for 67%–81% of the total impact. Similar to PED, milk powder is responsible for most of the GWP related to the raw materials. Manufacturing is also an important contributor (8%–16%) while packaging has a notable share for chocolate countlines and chocolates in bag (8%–13%). Its contribution for moulded chocolate is lower (8%). These results exclude land-use change for cocoa beans cultivation which is considered in the sensitivity analysis (see section 3.3.2).

Fossil fuel depletion (FFD): Fossil fuel depletion ranges from 24–31 MJ/kg (Fig. 3c), with chocolates in bag having the highest impact and the other two product depleting a similar amount of resources (23 and 24 MJ/kg). The main hotspots are milk powder (33%–48%), chocolate production (13%–26%) and packaging (7%–21%).

Ozone depletion (OD): The chocolates in bag have the highest and the countlines the lowest OD: 206 and 148 µg CFC-11 eq./kg, respectively (Fig. 3d). The impact from the moulded chocolate is 170 µg CFC-11 eq./kg. The most relevant life cycle stages are the raw materials (61%–71%), transport (13%–15%) and packaging (9%–22%). The production of milk powder, sugar, cocoa butter and cocoa powder are the highest contributing processes within the raw materials stage (Table S–2). The vast majority of OD is caused by halogenated organic emissions from these stages.

Freshwater eutrophication (FE): As shown in Fig. 3e, chocolates in bag are the worst option with respect to FE (0.87 g P eq./kg); the other two products have nearly equal FE (0.64 g P eq./kg). The majority of the impact (57%–72%) is associated with the production of key ingredients, such as milk powder, sugar, flour and cocoa butter (Table S–2). The contribution of manufacturing and packaging is also significant, ranging between 12%–21% and 12%–29%, respectively.

Marine eutrophication (ME) is similar for milk chocolate and chocolates in bag (10–11 N eq./kg), whereas chocolate countlines have a 30% lower impact (Fig. 3f). The ME is almost entirely due to the raw materials production (97%–99%), with milk powder and sugar being the main contributors. This is largely due to nitrate (74%) and ammonia emissions (20%–21%) to marine water.

Human toxicity (HT) ranges from 1.66 kg 1,4 DCB eq./kg for the countlines to 2.03 kg 1,4 DCB eq./kg for chocolates in bag (Fig. 3g). The majority of the impact is related to the raw materials (77%–85%), specifically milk powder and sugar; in the case of chocolate countlines, flour also has a significant impact share (14%). HT is mainly due to the emissions of phosphorus (42%–48%) and manganese (16%–17%), followed by zinc (9%) and chlorine (6%).

Terrestrial ecotoxicity (TET): Moulded and chocolates in bag have the highest TET, estimated at 31 and 30 g 1,4–DCB eq./kg, respectively, while that of the chocolate countlines is equal to 23 g 1,4–DCB eq./kg (Fig. 3h). The raw materials cause the majority of this impact (90%–92%), with the rest attributed to transport (7%–9%). Milk powder, sugar, palm oil and cocoa butter are the most

significant contributors among the raw materials (Table S–2). TET is mainly due to pesticides (69%) used in the agriculture, followed by chlorine (15%–17%) and copper (5%–6%) released along the life cycle.

Freshwater ecotoxicity (FET): As indicated in Fig. 3i, FET is highest for milk chocolate (133 g 1,4–DCB eq./kg), followed closely by chocolates in bag (131 g 1,4–DCB eq./kg). The impact from the countlines is around 25% lower (101 g 1,4–DCB eq./kg). Like TET, the main cause of this impact are the raw materials (91%–96%), with more than a half associated with cocoa cultivation. Milk powder (19%–21%) and sugar (11%) also have noteworthy contributions. FET can be traced back to copper, zinc and phosphorus releases as well as to pesticides used in agriculture.

Marine ecotoxicity (MET): Milk chocolate has the highest MET, followed by chocolates in bag, estimated at 121 and 117 g 1,4–DCB eq./kg, respectively. By comparison, chocolate countlines have an impact of 89 g/kg (Fig. 3j). Like the other two ecotoxicity impacts, MET is mainly due to the raw materials (87%–93%), of which more than 50% is also associated with cocoa production. Copper and zinc releases are the main environmental burdens causing this impact.

Terrestrial acidification (TA): As can be seen in Fig. 3k, the lowest TA was estimated for the countlines (46 g SO_2 eq./kg) and the highest for chocolates in bag (72 g SO_2 eq./kg), with the impact of moulded chocolates in between (65 g SO_2 eq./kg). The raw materials are again the main hotspot (92%–96%), with the milk powder production contributing most of it (89%–90%). The main environmental burdens are emissions of ammonia (84%–87%), nitrogen oxides (5%–7%) and sulphur dioxide (7%–9%).

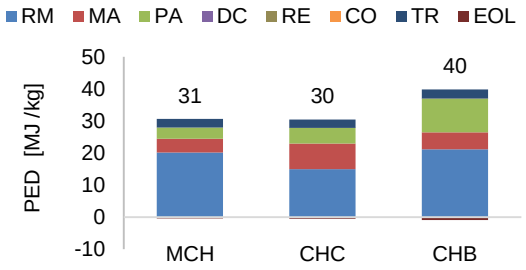
Land use and transformation: Three types of land were considered: agricultural, urban and natural. Chocolates in bag have the highest and the countlines the lowest impacts on land across the three types (Fig. 3l-n). As expected, the impact on agricultural and natural land is largely due to the cultivation of raw materials (71%–99%). Milk powder contribute most to the land use and transformation, followed by sugar (Table S–2). This is due to the land occupation for pastures (50%–57%) and for arable land (38%–44%); urban land occupation is mainly related to industrial buildings and roads network.

Photochemical oxidant formation (POF): Chocolates in bag have the highest POF (13 g NMVOC eq./kg) while the impacts of the other two products are slightly lower (9–11 g NMVOC eq./kg). As can be inferred from Fig. 3o, the raw materials contribute 70%–79% to the total and transport 9%–11%); for chocolates in bag, the share of packaging is also significant (15%). The most relevant activities for POF are milk powder (33%–42%) and sugar (19%–22%). The main POF burdens are emissions of nitrogen oxides (57%–59%), carbon monoxide (14%–17%) and non-methane volatile organic compounds (9%).

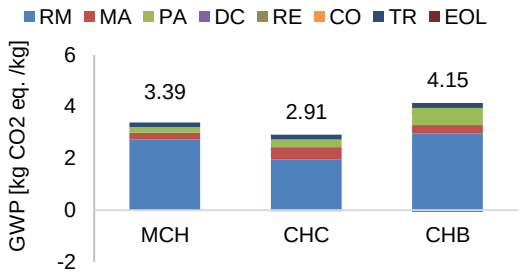
Mineral depletion (MD): Mineral depletion is depicted in Fig. 3p showing that chocolates in bag have the highest (156 g Fe eq./kg) and the countlines the lowest (115 g Fe eq./kg) impact. For all three types of chocolate, this is mainly due to the raw materials (71%–88%), followed by manufacturing (7%–13%) and packaging (7%–17%). Among the raw materials, cocoa butter and liquor together contribute more than a third and the milk powder another thirds. MD is mainly due to the depletion of chromium, copper, iron and nickel.

Water consumption: As can be seen in Fig. 3q, moulded chocolates consume most water (11,372 l/kg), followed by chocolates in bag (10,484 l/kg) and the countlines (7633 l/kg). However, the majority of that is green water which is entirely due to the raw materials. For the blue water consumption, chocolates in bag are the worst option, requiring 175 l/kg, while moulded chocolate has the lowest consumption (95 l/kg); the countlines use 122 l/kg. The main consumers of blue water are packaging (44%–65%), the raw materials (24%–43%) and manufacturing (6%–11%).

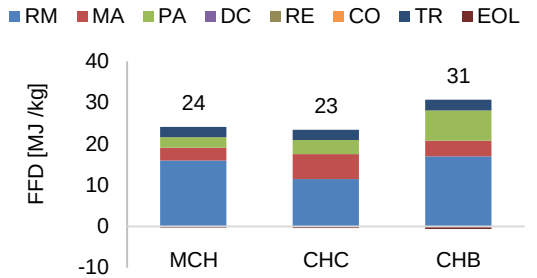
Water footprint (WF): The results in Fig. 3r show that chocolates in bag have the highest WF (63 l/kg), followed by chocolate countlines (43 l/kg) and moulded chocolate (31 l/kg). As the WF considers only blue water, packaging is the main hotspot (55%–73%), followed by the raw materials production (16%–30%) and manufacturing (7%–13%).



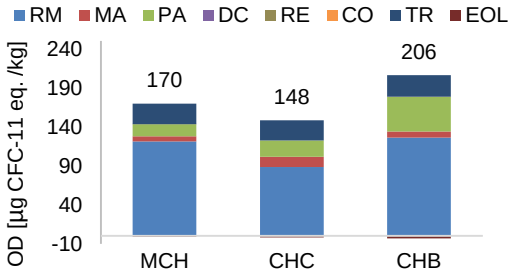
a) Primary energy demand



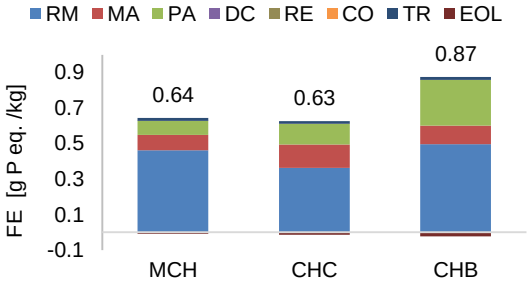
b) Global warming potential



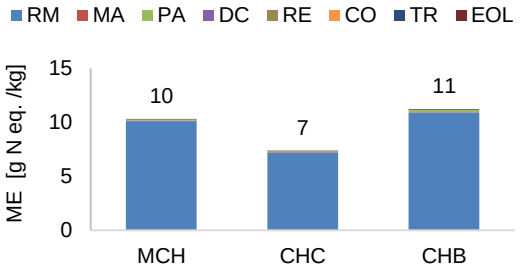
c) Fossil fuel depletion



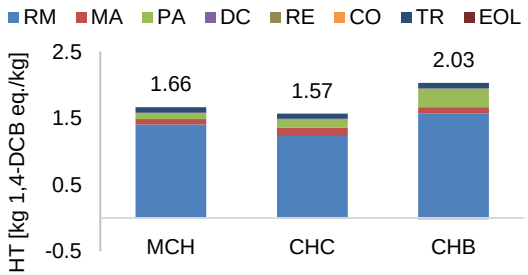
d) Ozone layer depletion



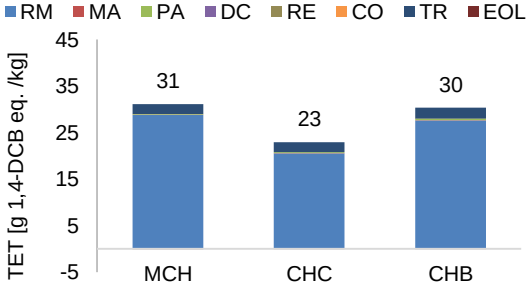
e) Freshwater eutrophication



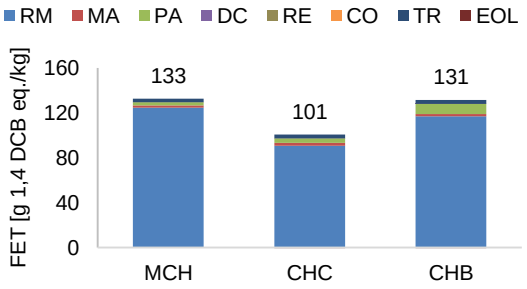
f) Marine eutrophication



g) Human toxicity



h) Terrestrial ecotoxicity



i) Freshwater ecotoxicity

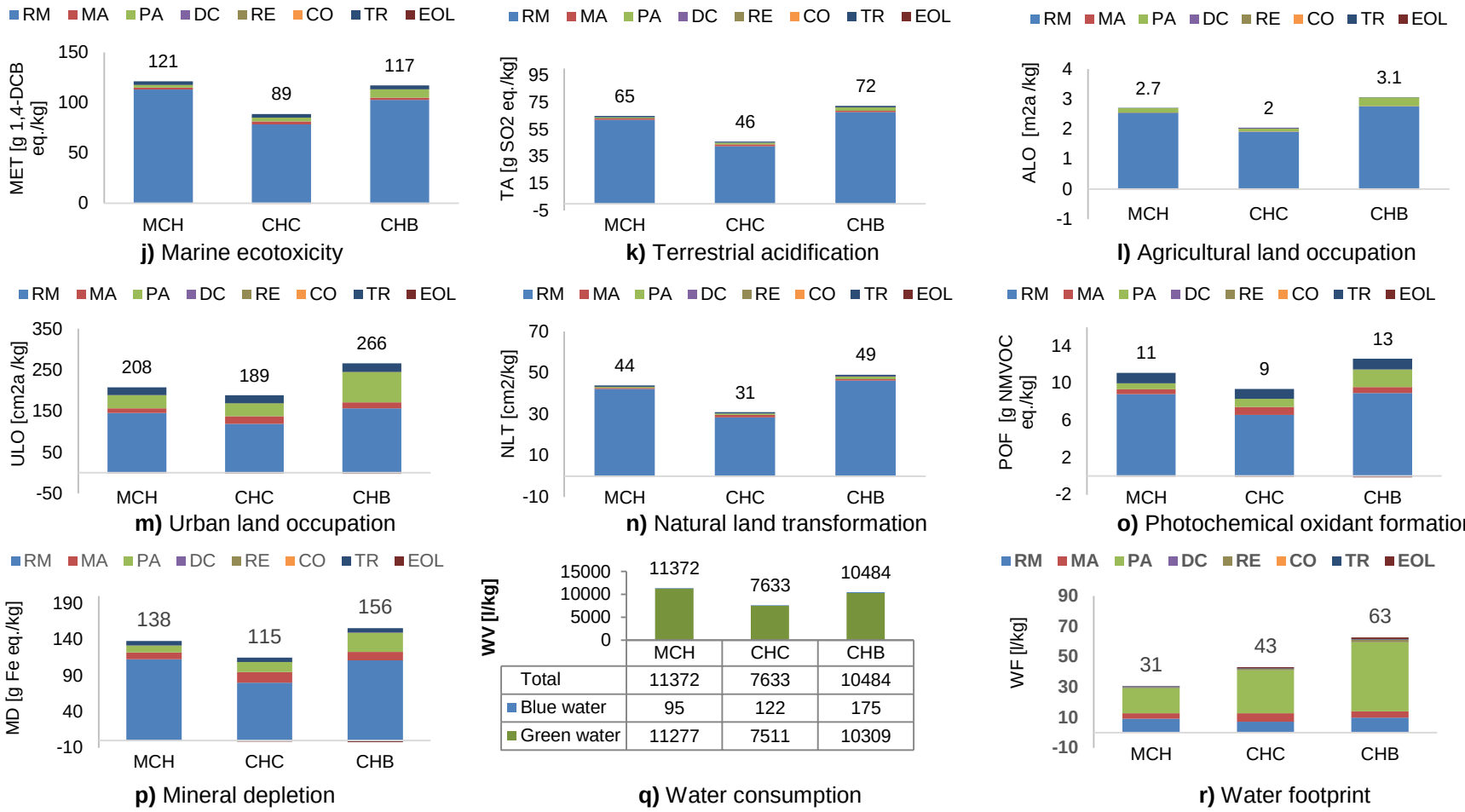


Fig. 3. Environmental impacts of different chocolate products showing contribution of different life cycle stages
[MCH: Moulded chocolate; CHC: chocolate countlines; CHB: chocolate in bag. RM: Raw materials; MA: Manufacturing (of chocolates); PA: Packaging: DC: Distribution centres and retailers; RE: Recycling; CO: Co-products; TR: Transport; EOL: end of life. DCB: dichlorobenzene].

3.2 Comparison of results with literature

As mentioned in the introduction, a limited number of LCA studies of chocolates are available in the literature, with most focusing on dark chocolate. Hence, direct comparison of the results with those studies is not possible. The only study that is relevant to the current work is that by Busser & Jungbluth (2009) which considered the environmental impacts of milk chocolate bars (moulded chocolate) manufactured and consumed in Europe. Although the authors estimated ten environmental impacts (albeit not using the ReCiPe method), only the value for GWP was available in the public domain. This shows a remarkable agreement with the estimate obtained here, being only 6% higher: 3.6 vs 3.39 kg CO_2 eq./kg. This difference is mainly due to different transport distances and the energy mix. There is also a good agreement between the PED estimates in this study (31–40 MJ/kg) and across all other studies (33–40 MJ/kg) as energy consumption is not so much affected by the type of chocolate. All the studies also found that the cultivation of cocoa beans was the main environmental hotspot, followed by chocolate manufacturing and packaging. This is in agreement with the findings of the current study.

3.3 Sensitivity analysis

Given the significant contribution of the raw materials to the impacts, the sensitivity analysis explores the effect on the results of the following aspects:

- the amount of raw milk used to produce milk powder;
- land-use change (LUC) related to cocoa production;
- losses of raw materials during chocolate production;
- sources of data for cocoa beans cultivation; and
- mass allocation instead of the economic.

Furthermore, as chocolate production and packaging were also significant contributors to some impacts, the sensitivity analysis also considers different energy consumption in the chocolate production process and losses of packaging during their manufacture. The results are discussed in turn in the next sections; for further detail, see Tables S-3.1–S-3.3.

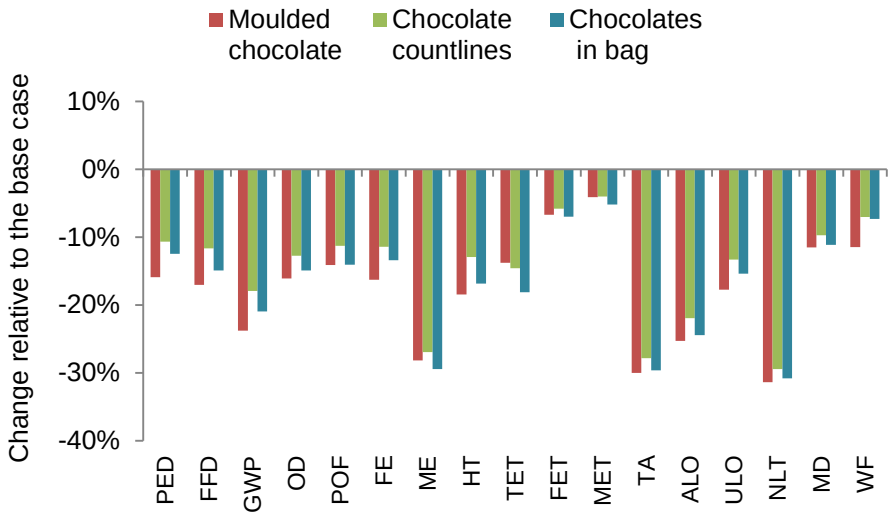
3.3.1 Amount of raw milk used to produce milk powder

The amount of raw milk required to produce milk powder varies among different studies. In the base case analysis, the data from Scottish Government (2011) were used which specified that 7.69 kg raw milk was required to produce 1 kg of milk powder. Finnegan et al. (2017) reported two different values: 5.12 and 9.22 kg of raw milk/kg milk powder. These two values are considered as part of the sensitivity analysis and the results are shown in Fig. 4.

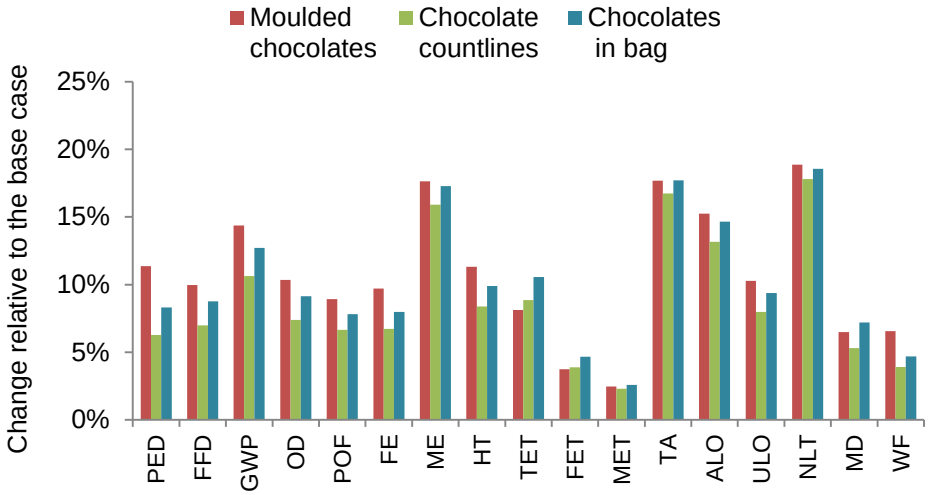
Reducing the amount of milk by 33% (from 7.69 to 5.12 kg) reduces the impacts by 5%-30% relative to the base case (Fig. 4a). The geatest reductions are found for marine eutrophication, terrestrial acidification, global warming potential and natural land transformation. However, if the amount of milk is increased by 44% (to 9.22 kg), the impacts increase from 3%-19% (Fig. 4b). Therefore, most impacts are sensitive to this variable.

3.3.2 LUC related to cocoa production

As cocoa production is increasing due to a growing demand for chocolate, it is important to consider the effect of LUC on climate change. Using DEFRA (2009) data for LUC for cocoa cultivation, the results in Fig. 5 indicate that there is a 3–4 fold increase in GWP in comparison to the base case in which no LUC was considered. More than 70% of the total impact is now due to cocoa butter and liquor as opposed to the base case where milk powder was the most significant contributor. Thus, the effect of LUC is very significant and should be considered on a case-to-case basis, depending on where the cocoa is sourced from and if the LUC was involved. However, the data for cocoa LUC should be treated with caution due to a high uncertainty, as acknowledged by DEFRA (2009).



a) Lower amount of raw milk compared to the base case (5.12 vs 7.69 l/kg milk powder).



b) Higher amount of raw milk compared to the base case (9.22 vs 7.69 l/kg milk powder.

Fig. 4. The effect on the impacts of the amount of raw milk used for producing milk powder [For the impacts nomenclature, see Fig. 3].

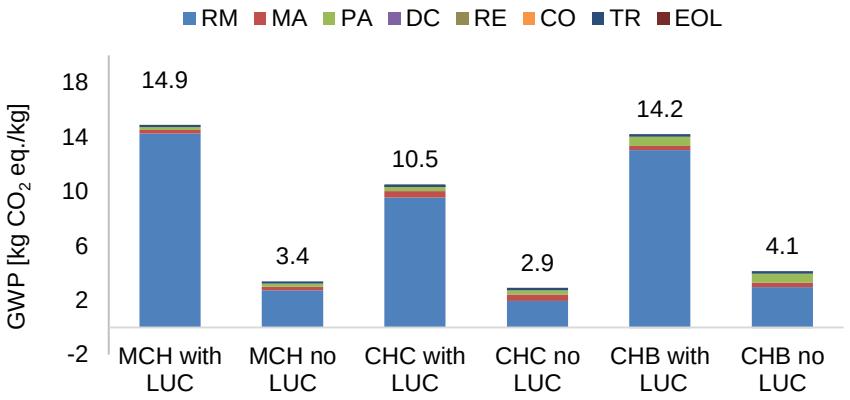


Fig. 5. Global warming potential (GWP) of three types of chocolate considering the land-use change (LUC) [For the acronyms, see Fig. 3].

3.3.3 Losses of raw materials during chocolate production

To evaluate the effect of raw material losses in the manufacturing process, the loss of 2% assumed in the base case was increased first to 5% and then to 10%. The latter is unlikely as it would represent significant financial losses but is considered nevertheless to find out how sensitive the results are to this parameter. The results suggest that increasing the losses to 5% increases the impacts by 2%–5% for the moulded chocolate and the countlines and by 3%–11% for chocolates in bag (see Table S–3.1). The impacts increase further with 10% losses, from 5% for fossil fuel depletion for the countlines to 23% for terrestrial ecotoxicity for chocolates in bag. Therefore, a small to moderate sensitivity can be observed for the raw material losses in the manufacturing process.

3.3.4 Data sources for cocoa beans cultivation

This part of the sensitivity analysis considers the effect on the impacts of using Ecoinvent V3.3 data for the cultivation of cocoa beans, instead of the data from EC (2015a) used in the base case. The results in Fig. 6 and Table S–3.2 show a significant change in the impacts, especially for energy consumption, ozone depletion, photochemical oxidant formation, eutrophication and human toxicity. The effect is particularly pronounced for the moulded chocolates, where some impacts increase by more than 100%. On the other hand, marine ecotoxicity is lower by 14% for all three chocolate types. Thus, as often happens in LCA, different sources of data for key impact contributors can change the results significantly and should be considered carefully.

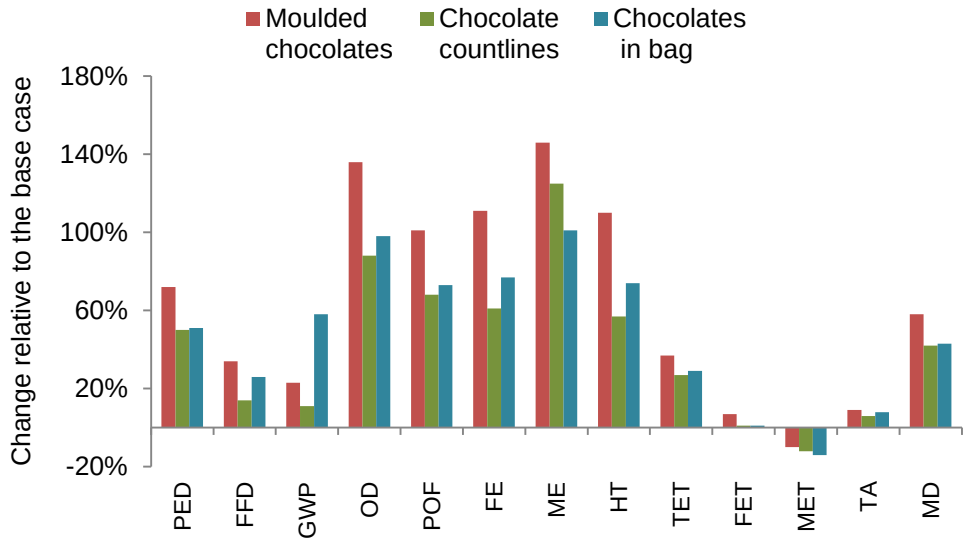


Fig. 6. The effect on the impacts of using a different data source for cocoa beans cultivation [Data in the base case are from EC (2015a) and data used in the sensitivity analysis are from Ecoinvent V3.3 (Ecoinvent, 2016). For the impacts nomenclature, see Fig. 3].

3.3.5 Economic vs mass allocation

In the base case, economic allocation was used for the co-products of cocoa, milk powder and wheat flour. As shown in Fig. 7, using mass allocation instead changes the impact by less than 2% compared to the base case. Hence, the choice of allocation method has no significant effect on the results for the products considered.

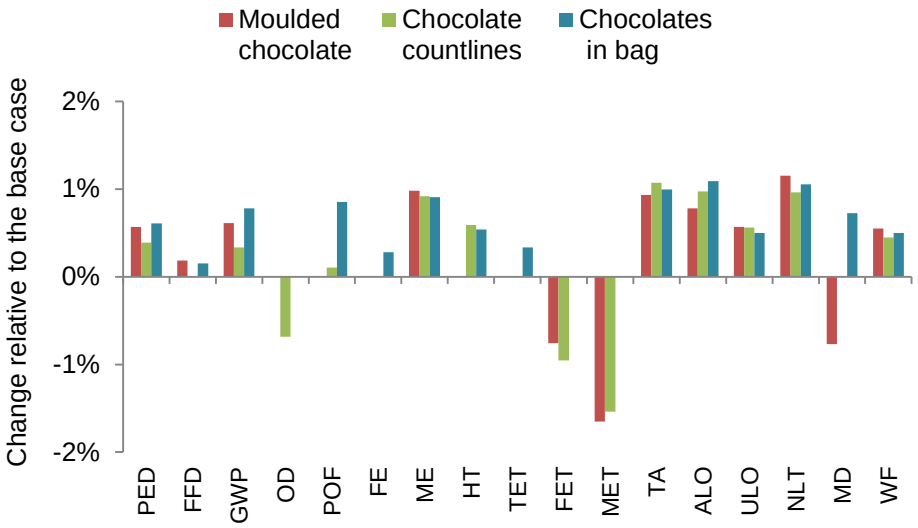


Fig. 7. The effect on the impacts of mass allocation compared to economic allocation [For the impacts nomenclature, see Fig. 3].

3.3.6 Energy consumption for chocolate production

Two options were considered for energy consumption in the manufacturing process: the first assumes a 50% increase in energy consumption relative to the base case and the second a 100% increase. The results in Fig. 8 show that the chocolate countlines are most affected by the variations in energy consumption while the effect on the other two products is smaller and similar to each other. For the 50% higher energy consumption (Fig. 8a), the impact categories most affected are primary energy demand (7%–13%), fossil fuel depletion (6%–13%), global warming potential (4%–8%) and freshwater eutrophication (6%–11%). The effect on the rest of the impacts is negligible.

If the energy use is doubled on the base case (Fig. 8b), the energy-related categories increase by more than 20% in the case of chocolate countlines. Additionally, freshwater eutrophication and global warming potential rise by more than 10% for this product category. Thus, the sensitivity of impacts with respect to the energy consumption is moderate.

3.3.7 Packaging losses

Considering the loss of packaging in their manufacturing process in the range from 2% to 10% has no influence on the impacts categories, except for a small effect on water consumption. As can be seen in Fig. 9, the increase in blue water consumption and the related water footprint becomes notable only at a 10% loss (4.5%-6%). However, such a high rate of packaging loss is probably unrealistic due to the associated financial penalties. Hence, it can be concluded that the results are not sensitive to packaging losses.

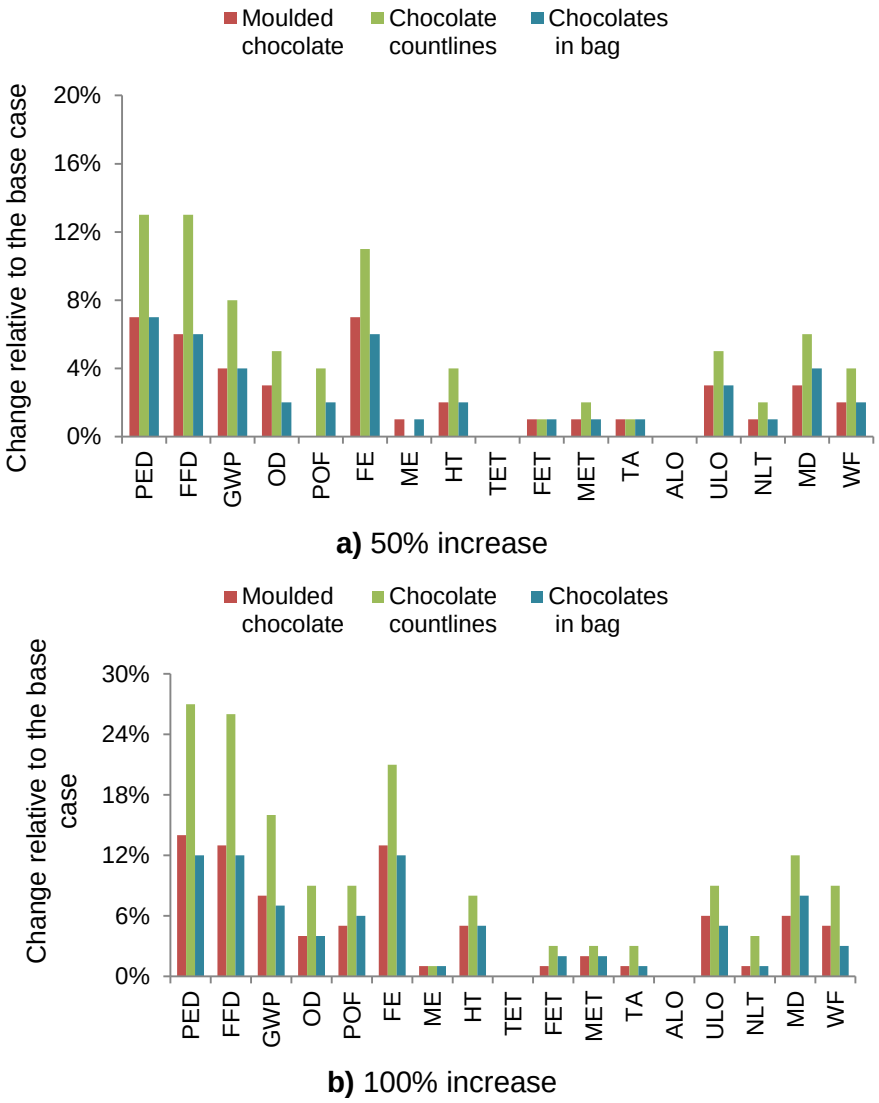


Fig. 8. The effect on the impacts of increasing energy consumption in the manufacturing processes
[For the impacts nomenclature, see Fig. 3].

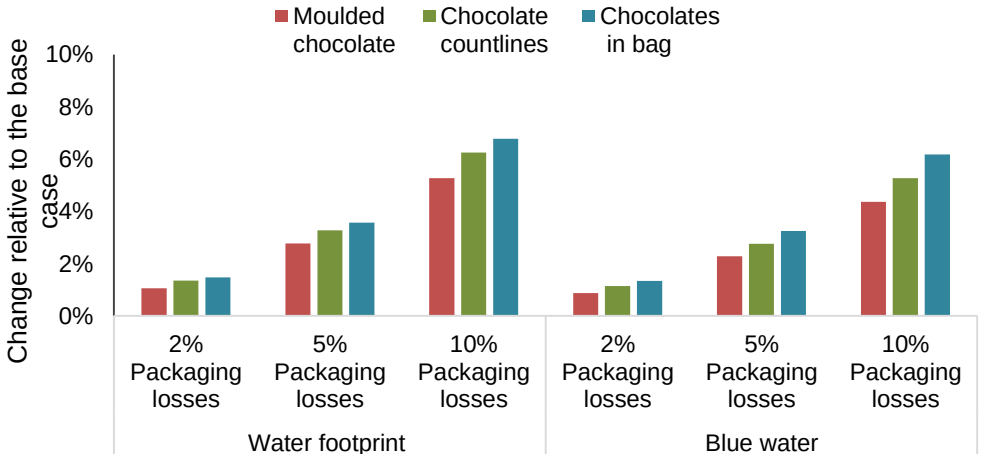


Fig. 9 The effect on the water consumption of packaging losses
[No packaging losses assumed in the base case].

3.4 Uncertainty analysis

An uncertainty analysis was carried out to assess the robustness of the results against a plausible range of variations in different LCI parameters. For this purpose, the variations in the following parameters influencing the results were considered:

- the amount of raw milk required to produce milk powder: 5.12–9.22 kg/kg milk powder;
- losses of raw materials in the manufacturing process: 2%–10% of the final product; and
- energy consumption in the manufacturing process: a 100% increase on the base case.

Uniform distributions were assumed for all parameter values due to a lack of information on their actual distributions. Monte Carlo simulations with 10,000 iterations and 90% confidence intervals were performed to estimate the fluctuations of the impacts.

The results in Fig. 10 show that the impacts vary from 3% to 20% relative to the base case. The greatest variations of 15%-20% were found for primary energy demand, global warming, marine eutrophication, human toxicity, terrestrial acidification, agricultural land occupation and natural land transformation. Fluctuations of up to 10% can be observed for fossil fuel and ozone depletion, photochemical oxidant formation, freshwater eutrophication, terrestrial ecotoxicity and urban land occupation. Therefore, it can be concluded that the results are robust, given the significant variations in the parameters considered.

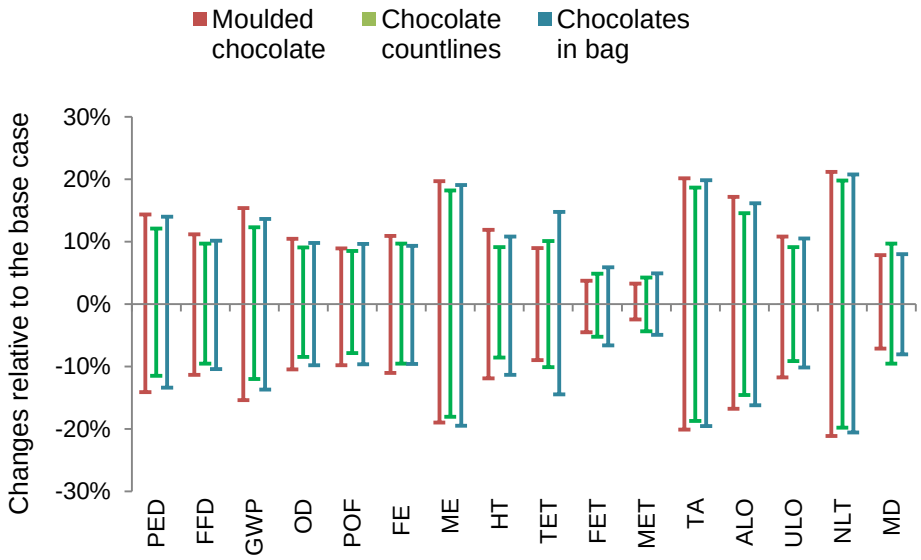


Fig. 10. The results of the uncertainty analysis showing fluctuation of the impacts with different parameters relative to the base case
[For the impacts nomenclature, see Fig. 3].

3.5 Environmental impacts of chocolate consumption in the UK

This section analyses the environmental impacts of annual chocolate consumption in the UK based on the results presented in the previous sections and the amount of the products considered sold annually. The data for the latter were not available and were estimated in this study based on the market share of the different product categories (Key Note, 2015) and their market prices obtained from major retailers as part of this research. As a result, the annual sales volume of different chocolate product categories were estimated as follows:

- moulded chocolates: 112,667 tonnes;
- chocolate countlines: 302,833 tonnes;
- chocolates in bag: 157,108 tonnes; and
- other chocolate confectionary: 63,000 tonnes.

Thus, a total of 635,608 tonnes of various chocolate products were estimated to be consumed annually in the UK. Scaling up the impacts per kg of different products discussed in the previous sections to their respective annual consumption gives the total annual impacts presented in Fig. 11. In the absence of data for the category "other chocolate confectionary", a conservative approach was taken assuming that their impact in each category is the same as the highest impact of the other three products for that category.

It can be seen in Fig. 11 that, for example, the sectoral primary energy consumption amounts to 21,370 TJ/yr and the GWP to 2.1 Mt CO_2 eq./yr. The former represents 4.7% of the overall energy consumed in the food and drink sector, based on the estimates for the total primary energy consumption in the UK food and drink sector of 126 TWh/yr (DEFRA, 2006). However, the latter only considers energy used in production processes and excludes the energy consumption in the rest of the life cycle. Thus, the estimates for energy use in the UK food and drink sector are underestimated, which means that the contribution of the chocolate sector to the total sectoral energy consumption is even lower. Therefore, energy consumption is not a significant factor for the chocolate sector.

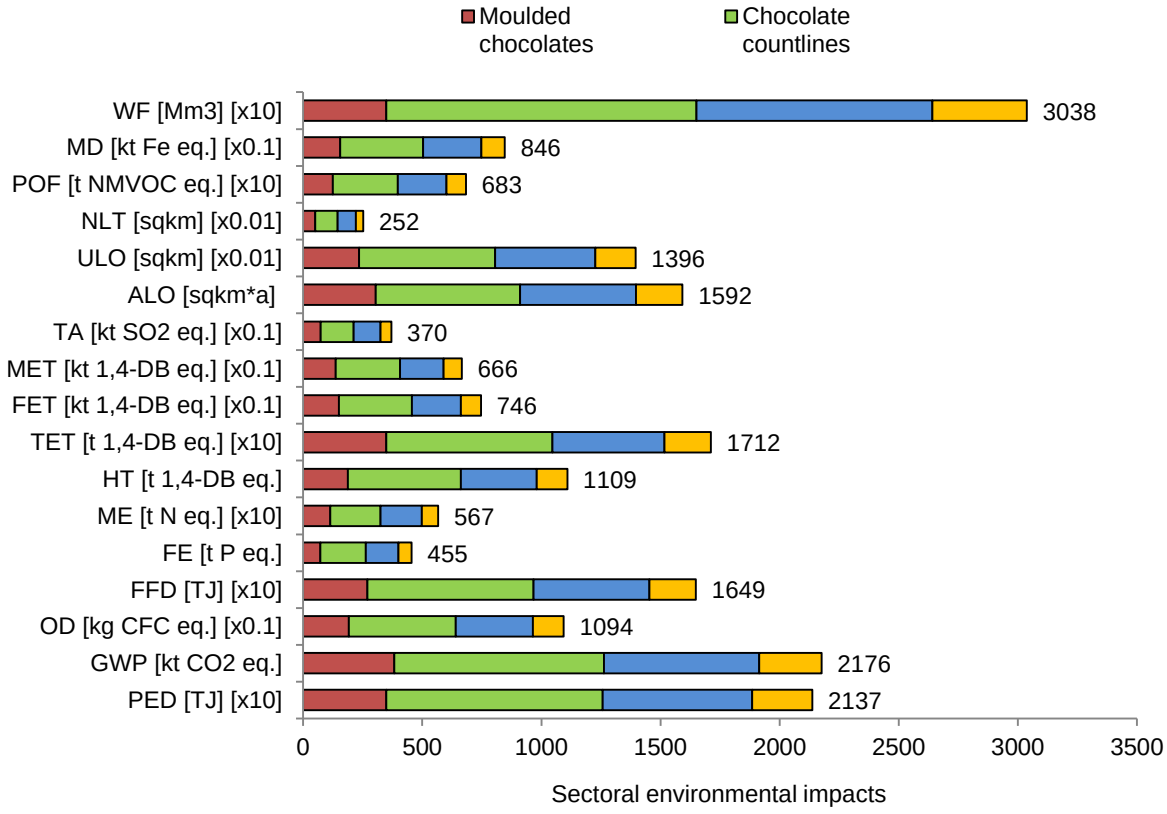


Fig. 11. Annual environmental impacts of chocolate production and consumption in the UK [Some impacts have been scaled to fit. To obtain the original values, multiply by the factor in brackets for relevant impacts. For the impacts nomenclature, see Fig. 3].

However, the contribution of greenhouse gas (GHG) emissions from the chocolate sector to the total UK emissions is more notable. Taking the consumption perspective and considering the total UK GHG emissions of around 550 Mt CO_2 eq. per year (Druckman & Jackson, 2009), the chocolate subsector contributes 0.38% to the total national GWP. According to the above authors, the contribution of the food sector to the total UK emissions is 15%, which means that the chocolate sector is responsible for 2.4% of the total UK food-related GWP. However, it should be noted that the data in Druckman & Jackson are from dated (from 2004) and are also by the authors' own admission underestimated due to the method used. Hence, the estimates of the contribution of the chocolate sector to the total should be

interpreted with this in mind. The other impacts are more difficult to put into context as there are no sectoral or national data.

Fig. 11 also shows that chocolate countlines have the highest contribution to all the impact categories, which ranges from 37%–43% of the total. This is followed by chocolates in bag with the contributions of 28%–33%. The contributions from moulded chocolates and other chocolate confectionary are similar to each other and make up the rest of the impacts.

3.6 Improvement opportunities

According to the results, the production of milk powder and cocoa derivatives, along with the manufacturing process, are the main contributors to the impacts and should therefore be targeted for improvements. These are considered below. Packaging has also been identified as a significant contributor to some of the impacts and should also be subject to improvements. However, packaging is not considered here due to a lack of data for alternative packaging that could be used instead while preserving functionality.

Since the vast majority of the milk powder impacts are associated with the raw milk production at farm, two possible improvement opportunities related to the raw milk production are considered: i) manure composting instead of leaving it on the land as in the base case; and ii) a 20% energy reduction in the milk parlour due to more efficient energy management. The results suggest that through these improvements the GWP of moulded chocolate would be reduced by 12%, fossil fuel depletion by 5% and freshwater eutrophication by 4% (Table S–4). For chocolates in bag, 11% of GWP and 5% of fossil fuel depletion would be avoided. The GWP savings for the chocolate countlines would be around 9% but the other categories would not be influenced. Thus, in accordance with the sensitivity analysis results, a lower amount of raw milk used for producing milk powder could mitigate the environmental impacts more effectively as a result of more efficient manufacturing process. A further improvement option that could be considered is to modify the cows' diet to reduce methane emissions from enteric fermentation. For example, Roibas et al. (2016) considered the effect on the emissions of the addition of linseeds to the feed and found that the GWP of milk was reduced by 10%. Applying this potential reduction to the milk production in this study would reduce the overall GWP of chocolates by 5%–7%.

Cocoa butter and liquor have significant ecotoxicity impacts. According to Ntiamoah & Afrane (2008), these could be reduced through the following measures: i) use of organic fertilisers combined with their more efficient application; ii) a 50% reduction of conventional fertiliser use; and iii) a 50% reduction in the amount of pesticides used. However, yield decreases should also be considered if applying these measures. Further consideration of these is beyond the scope of this paper.

Improvements in the manufacturing process considered here are related to a more efficient energy use, assuming a 15%-25% reduction. These improvements could be achieved through implementation of integrated energy management systems or more advanced and innovative production technologies. The results suggests that energy savings of more than 20% could lead to reductions in most impacts but these would be small, ranging from 3% for the moulded and chocolates in bag to 5% for the countlines.

4 Conclusions

This study assessed the life cycle environmental impacts associated with the main chocolate products produced and consumed in the UK: moulded chocolates, chocolate countlines and chocolates in bag. The results suggest that the raw materials production is the major hotspot across all impact categories. Packaging and manufacturing also influence the impacts, while transport has a significant contribution to ozone depletion, fossil fuel depletion and formation of photochemical oxidants. The impacts from the raw materials are largely due to milk

powder production, while sugar and cocoa derivatives are significant contributors to some of the impacts. Therefore, the production of these raw materials should be targeted for environmental improvements, together with the chocolate manufacturing process and packaging. For example, composting the dairy manure, reducing energy consumption in milk parlour by 20% and supplementing cows' feed with linseeds could together reduce the GWP of chocolates by 14%-19%.

The sensitivity analysis shows that the results for global warming potential are very sensitive to land-use change associated with cocoa production, increasing the impact of chocolate products by a three to four times if LUC is involved. The assumptions on the amount of milk used to produce milk powder also influence the results significantly, while the effect of the assumptions for energy consumption and losses of raw materials in the manufacturing process is moderate. The influence of using mass instead of economic allocation is negligible. The uncertainty analysis demonstrates that the obtained results are robust.

The impacts estimated per kilogram of each product type were scaled up to the annual consumption of chocolate in the UK to evaluate the overall environmental implications. The results suggest that around 21 TJ of primary energy is consumed and 2.1 Mt CO_2 eq. are emitted annually to produce and supply 635.6 kt of chocolate products to UK consumers. The latter represents 2.4% of the GHG emissions from the whole food and drink sector in the UK. Among the product types considered, chocolate countlines have the highest contribution to the total (37%–43%), followed by chocolates in bag (28%–33%). Moulded chocolates and the other chocolate confectionary make up the rest of the impacts, with a roughly equal share each. The results of this work can be used by policy makers and producers to target the identified hotspots for improvements and monitor future progress of the sector. The findings will also be of interest to consumers, helping them make informed choices towards sustainable consumption of chocolate products.

Acknowledgement

This research has been founded by the UK Engineering and Physical Sciences Research Council, EPSRC (Grant no. EP/F007132/1). This funding is gratefully acknowledged.

Appendix A. Supplementary data

The Supporting information includes data on the contribution of different life cycle stages to the total impacts and the results of the sensitivity and improvement opportunities analyses.

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Environmental impacts of chocolate production and consumption in the UK

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Supplementary information

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Table S-1 Contribution of different life cycle stages to the total impacts

		Life cycle stages							
Impact categories	**Chocolate types**	**Raw materials**	**Manufacturing**	**Packaging**	**Distribution centre**	**Retail**	**Consumption**	**End of life**	**Transport**
Primary energy demand (PED)	Moulded chocolates	66%	14%	11%					9%
	Countlines	49%	26%	16%					9%
	Chocolates in bag	53%	13%	26%					7%
Fossil fuel depletion (FFD)	Moulded chocolates	66%	13%	11%					10%
	Countlines	49%	25%	15%					11%
	Chocolates in bag	55%	12%	24%					8%
Global warming potential (GWP)	Moulded chocolates	81%	8%	6%					
	Countlines	67%	16%	11%					
	Chocolates in bag	72%	7%	16%					
Ozone depletion (OD)	Moulded chocolates	71%		9%					15%
	Countlines	60%	9%	14%					17%
	Chocolates in bag	61%		22%					13%
Photochemical oxidant	Moulded chocolates	79%		6%					10%
formation (POF)	Countlines	70%	9%	9%					11%
	Chocolates in bag	70%		15%					9%
Freshwater eutrophication (FE)	Moulded chocolates	72%	13%	12%					
	Countlines	58%	21%	19%					
	Chocolates in bag	57%	12%	29%					
Marine eutrophication (ME)	Moulded chocolates	98%							
	Countlines	97%							
	Chocolates in bag	97%							
Human toxicity (HT)	Moulded chocolates	85%		6%					
	Countlines	78%	8%	9%					
	Chocolates in bag	77%		14%					
Terrestrial ecotoxicity (TET)	Moulded chocolates	92%							7%
	Countlines	90%							9%
	Chocolates in bag	91%							7%

Table S-1 Continued

		Life cycle stages							
Impact categories	**Chocolate types**	**Raw materials**	**Manufacturing**	**Packaging**	**Distribution centre**	**Retail**	**Consumption**	**End-of-life**	**Transport**
Freshwater ecotoxicity (FET)	Moulded chocolates	94%							
	Countlines	90%							
	Chocolates in bag	90%							
Marine ecotoxicity (MET)	Moulded chocolates	93%							
	Countlines	88%							
	Chocolates in bag	87%							
Terrestrial acidification (TA)	Moulded chocolates	96%							
	Countlines	92%							
	Chocolates in bag	93%							
Agricultural land occupation (ALO)	Moulded chocolates	94%		5%					
	Countlines	93%		6%					
	Chocolates in bag	90%		9%					
Urban land occupation (ULO)	Moulded chocolates	70%	5%	15%					9%
	Countlines	63%	9%	17%					10%
	Chocolates in bag	59%		28%					8%
Natural land transformation (NLT)	Moulded chocolates	96%							
	Countlines	92%							
	Chocolates in bag	94%							
Mineral depletion (MD)	Moulded chocolates	82%	7%	7%					
	Countlines	70%	13%	12%					
	Chocolates in bag	71%	7%	17%					
Water footprint	Moulded chocolates	30%	12%	55%					
	Countlines	17%	13%	66%					
	Chocolates in bag	16%	7%	73%					

Table S-2 Contribution to the impacts of most relevant life cycle stages: raw materials, manufacturing and packaging

Impact categories	Chocolate types	Milk powder	Sugar	Flour	Cocoa butter	Cocoa mass	Palm oil	Manufacturing processes	Primary packaging	Secondary packaging
Primary energy demand (PED)	Moulded chocolates	47%	7%		6%			14%	7%	
	Countlines	31%	6%					26%	13%	
	Chocolates in bag	39%						13%	21%	
Fossil fuel depletion (FFD)	Moulded chocolates	48%	6%		6%			13%	6%	
	Countlines	33%						26%	11%	
	Chocolates in bag	42%						12%	18%	
Global warming potential (GWP)	Moulded chocolates	70%						8%	6%	
	Countlines	54%						16%	8%	
	Chocolates in bag	63%						8%	13%	
Ozone depletion (OD)	Moulded chocolates	46%	9%		9%	6%				
	Countlines	35%	9%		9%	7%		9%	10%	
	Chocolates in bag	42%	7%		7%	6			15%	
Photochemical oxidant formation (POF)	Moulded chocolates	42%	22%		6%					
	Countlines	33%	22%					9%	7%	
	Chocolates in bag	41%	19%					6%	11%	
Freshwater eutrophication (FE)	Moulded chocolates	48%	7%		9%	7%		13%	9%	
	Countlines	32%	6%		7%	6%		21%	16%	
	Chocolates in bag	39%	5%		7%	4%		12%	25%	
Marine eutrophication (ME)	Moulded chocolates	85%	10%							
	Countlines	79%	12%							
	Chocolates in bag	86%	9%							
Human toxicity (HT)	Moulded chocolates	54%	13%		7%					
	Countlines	38%	12%	14%				8%	7%	
	Chocolates in bag	49%	10%		6%			6%	11%	
Terrestrial ecotoxicity (TET)	Moulded chocolates	39%	20%		7%		21%			
	Countlines	35%	24%		6%		19%			
	Chocolates in bag	44%	20%		7%		16%			

Table S-2 Continued

Impact categories	Chocolate types	Milk powder	Sugar	Flour	Cocoa butter	Cocoa mass	Palm oil	Manufacturing processes	Primary packaging	Secondary packaging
Freshwater ecotoxicity (FET)	Moulded chocolates	19%	11%		35%	26%				
	Countlines	21%	11%		34%	19%				
	Chocolates in bag	21%	11%		34%	16%				
Marine ecotoxicity (MET)	Moulded chocolates	12%	9%		40%	30%				
	Countlines	16%	13%		31%	23%				
	Chocolates in bag	13%	9%		40%	23%				
Terrestrial acidification (TA)	Moulded chocolates	90%								
	Countlines	83%								
	Chocolates in bag	88%								
Agricaltural land occupation (ALO)	Moulded chocolates	76%	15%							
	Countlines	66%	17%							
	Chocolates in bag	73%	13%							
Urban land occupation (ULO)	Moulded chocolates	51%	7%					6%		12%
	Countlines	37%	7%	8%				10%		11%
	Chocolates in bag	44%	6%					6%	9%	19%
Natural land transformation (NLT)	Moulded chocolates	94%								
	Countlines	88%								
	Chocolates in bag	92%								
Mineral depletion (MD)	Moulded chocolates	34%	6%		23%	17%		7%		
	Countlines	27%	6%		18%	13%		13%	10%	
	Chocolates in bag	33%			20%	11%		7%	14%	
Water footprint	Moulded chocolates	25%						12%	52%	
	Countlines	12%						13%	64%	
	Chocolates in bag	13%						7%	69%	

Sensitivity analysis

Table S-3.1 Loss of ingredients

	Percentage change for 5% loss relative to the base case		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	4%	4%	5%
Agricultural land occupation (ALO	5%	5%	6%
Global warming potential (GWP)	4%	3%	4%
Fossil fuel depletion (FFD)	3%	2%	3%
Freshwater ecotoxicity (FET)	3%	3%	5%
Freshwater eutrophication (FE)	3%	3%	4%
Human toxicity (HT)	4%	4%	5%
Marine ecotoxicity (MET)	2%	3%	4%
Marine eutrophication (ME)	5%	5%	5%
Mineral depletion (MD)	3%	3%	4%
Natural land transformation (NLT)	5%	5%	5%
Ozone depletion (OD)	4%	3%	4%
Photochemical oxidant formation	4%	3%	6%
Terrestrial acidification (TA)	5%	5%	5%
Terrestrial ecotoxicity (TET)	4%	4%	11%
Urban land occupation (ULO)	4%	3%	5%

	Percentage change for 10% loss relative to the base case		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	9.0%	7.5%	11.4%
Agricultural land occupation (ALO	9.8%	9.3%	12.0%
Global warming potential (GWP)	8.6%	6.7%	8.6%
Fossil fuel depletion (FFD)	7.1%	4.8%	7.2%
Freshwater ecotoxicity (FET)	8.3%	7.6%	10.3%
Freshwater eutrophication (FE)	7.7%	5.7%	7.6%
Human toxicity (HT)	8.9%	7.7%	10.8%
Marine ecotoxicity (MET)	7.4%	6.9%	9.8%
Marine eutrophication (ME)	9.8%	9.5%	10.9%
Mineral depletion (MD)	7.7%	6.2%	8.7%
Natural land transformation (NLT)	9.7%	9.0%	9.7%
Ozone depletion (OD)	8.4%	6.2%	8.6%
Photochemical oxidant formation	8.4%	7.5%	12.0%
Terrestrial acidification (TA)	9.6%	9.2%	10.1%
Terrestrial ecotoxicity (TET)	9.0%	8.4%	23.5%
Urban land occupation (ULO)	8.5%	6.7%	10.0%

Table S-3.2 Different data source for cocoa beans cultivation

	Percentage change relative to the base case when using data from Ecoinvent V3.3		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	72%	50%	51%
Agricultural land occupation (ALO	245%	197%	176%
Global warming potential (GWP)	23%	11%	58%
Fossil fuel depletion (FFD)	34%	14%	26%
Freshwater ecotoxicity (FET)	7%	1%	1%
Freshwater eutrophication (FE)	111%	61%	77%
Human toxicity (HT)	110%	57%	74%
Marine ecotoxicity (MET)	-10%	-12%	-14%
Marine eutrophication (ME)	146%	125%	101%
Mineral depletion (MD)	58%	42%	43%
Natural land transformation (NLT)	3725%	3437%	2511%
Ozone depletion (OD)	136%	88%	98%
Photochemical oxidant formation	101%	68%	73%
Terrestrial acidification (TA)	9%	6%	8%
Terrestrial ecotoxicity (TET)	37%	27%	29%
Urban land occupation (ULO)	143%	87%	114%

Table S-3.3 Packaging losses

	Percentage change for 2% loss relative to the base case		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	0.21%	0.12%	0.17%
Agricultural land occupation (ALO)	0.11%	0.12%	0.18%
Global warming potential (GWP)	0.12%	0.08%	0.11%
Fossil fuel depletion (FFD)	0.00%	0.00%	0.00%
Freshwater ecotoxicity (FET)	0.04%	0.03%	0.05%
Freshwater eutrophication (FE)	0.24%	0.09%	0.13%
Human toxicity (HT)	0.12%	0.07%	0.10%
Marine ecotoxicity (MET)	0.05%	0.03%	0.05%
Marine eutrophication (ME)	0.02%	0.02%	0.02%
Mineral depletion (MD)	0.14%	0.10%	0.14%
Natural land transformation (NLT)	0.02%	0.02%	0.03%
Ozone depletion (OD)	0.19%	0.13%	0.19%
Photochemical oxidant formation (PC	0.11%	0.09%	0.12%
Terrestrial acidification (TA)	0.02%	0.02%	0.02%
Terrestrial ecotoxicity (TET)	0.01%	0.01%	0.02%
Urban land occupation (ULO)	0.30%	0.24%	0.40%
	Percentage change for 5% loss relative to the base case		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	0.00%	0.29%	0.42%
Agricultural land occupation (ALO)	0.26%	0.29%	0.45%
Global warming potential (GWP)	0.14%	0.19%	0.26%
Fossil fuel depletion (FFD)	0.01%	0.01%	0.01%
Freshwater ecotoxicity (FET)	0.05%	0.07%	0.12%
Freshwater eutrophication (FE)	0.20%	0.21%	0.32%
Human toxicity (HT)	0.14%	0.16%	0.26%
Marine ecotoxicity (MET)	0.05%	0.07%	0.12%
Marine eutrophication (ME)	0.03%	0.04%	0.06%
Mineral depletion (MD)	0.17%	0.24%	0.34%
Natural land transformation (NLT)	0.04%	0.05%	0.07%
Ozone depletion (OD)	0.26%	0.31%	0.47%
Photochemical oxidant formation (PC	0.15%	0.21%	0.29%
Terrestrial acidification (TA)	0.02%	0.04%	0.05%
Terrestrial ecotoxicity (TET)	0.03%	0.03%	0.06%
Urban land occupation (ULO)	0.62%	0.58%	0.98%
	Percentage change for 5% loss relative to the base case		
Impact categories	*Moulded chocolates*	*Chocolate countlines*	*Chocolates in bag*
Primary energy demand (PED)	0.45%	0.56%	0.80%
Agricultural land occupation (ALO)	0.49%	0.54%	0.85%
Global warming potential (GWP)	0.27%	0.36%	0.49%
Fossil fuel depletion (FFD)	0.01%	0.01%	0.02%
Freshwater ecotoxicity (FET)	0.10%	0.13%	0.22%
Freshwater eutrophication (FE)	0.38%	0.41%	0.61%
Human toxicity (HT)	0.27%	0.31%	0.49%
Marine ecotoxicity (MET)	0.10%	0.14%	0.22%
Marine eutrophication (ME)	0.06%	0.08%	0.11%
Mineral depletion (MD)	0.32%	0.46%	0.64%
Natural land transformation (NLT)	0.07%	0.09%	0.13%
Ozone depletion (OD)	0.50%	0.59%	0.89%
Photochemical oxidant formation (PC	0.29%	0.40%	0.55%
Terrestrial acidification (TA)	0.05%	0.08%	0.09%
Terrestrial ecotoxicity (TET)	0.05%	0.06%	0.11%
Urban land occupation (ULO)	1.17%	1.12%	1.86%

Table S-4 Improvement opportunities: manure composting and 20% energy reduction in the milk p

Impact categories	ıange relative to the base case for moulded chocolates[a]
Primary energy demand (PED)	-2%
Agricultural land occupation (ALO)	0%
Global warming potential (GWP)	-12%
Fossil Fuel depletion (FFD)	-5%
Freshwater ecotoxicity (FET)	2%
Freshwater eutrophication (FE)	-4%
Human toxicity (HT)	-1%
Marine ecotoxicity (MET)	1%
Marine eutrophication (ME)	0%
Metal depletion (MD)	-2%
Natural land transformation (NLT)	0%
Ozone depletion (OD)	-1%
Photochemical oxidant formation (F	-2%
Terrestrial acidification (TA)	-1%
Terrestrial ecotoxicity (TET)	-1%
Urban land occupation (ULO)	0%

Impact categories	ange relative to the base case for chocolate countlines[a]
Primary energy demand (PED)	-1%
Agricultural land occupation (ALO)	0%
Global warming potential (GWP)	-9%
Fossil Fuel depletion (FFD)	-3%
Freshwater ecotoxicity (FET)	2%
Freshwater eutrophication (FE)	-3%
Human toxicity (HT)	-1%
Marine ecotoxicity (MET)	1%
Marine eutrophication (ME)	0%
Metal depletion (MD)	-1%
Natural land transformation (NLT)	-1%
Ozone depletion (OD)	-1%
Photochemical oxidant formation (F	-1%
Terrestrial acidification (TA)	-1%
Terrestrial ecotoxicity (TET)	0%
Urban land occupation (ULO)	0%

Impact categories	Change relative to the base case for chocolates in bag[a]
Primary energy demand (PED)	-2%
Agricultural land occupation (ALO)	0%
Global warming potential (GWP)	-11%
Fossil Fuel depletion (FFD)	-5%
Freshwater ecotoxicity (FET)	2%
Freshwater eutrophication (FE)	-4%
Human toxicity (HT)	-1%
Marine ecotoxicity (MET)	2%
Marine eutrophication (ME)	-1%
Metal depletion (MD)	-1%
Natural land transformation (NLT)	-1%
Ozone depletion (OD)	-2%
Photochemical oxidant formation (F	-2%
Terrestrial acidification (TA)	-1%
Terrestrial ecotoxicity (TET)	-1%
Urban land occupation (ULO)	0%

[a] Negative values represent a reduction and positive an increase in impacts.