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An environmental evaluation of food supply chain using life cycle assessment: A case study on gluten free biscuit products

López Isabel Noya [a], Vasileia Vasilaki [c], Valentina Stojceska [b, d, *], Sara González-García [a], Chantelle Kleynhans [b], Savvas Tassou [d], Maite Teresa Moreira [a], Evina Katsou [c, e]

[a] University of Santiago de Compostela, Department of Chemical Engineering, School of Engineering, 15782, Santiago de Compostela, Spain
[b] Brunel University London – College of Engineering, Design and Physical Sciences, Department of Mechanical and Aerospace Engineering, Uxbridge, Middlesex, UK
[c] Brunel University London – College of Engineering, Design and Physical Sciences, Department of Civil & Environmental Engineering, Uxbridge, Middlesex, UK
[d] Brunel University London – Institute of Energy Futures – Centre for Sustainable Energy in Food Chains, Uxbridge, Middlesex, UK
[e] Brunel University London – Institute of Environment, Health and Societies, Uxbridge, Middlesex, UK

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ABSTRACT

This paper assesses the environmental profile of the biscuit supply chain for producing high quality gluten-free biscuits. Three different types of biscuits were considered. The assessment followed a cradle-to-grave approach applying the ISO standards in compliance with the Product Category Rules (PCR) defined within EPD (Environmental Product Declaration) for bakery products. Analogous environmental profiles were implemented for assessing the products: It was found that the main *hotspot* in all impact categories was ingredients production with the range contribution from 22.2% to 84.9%, followed by transportation. Initial hypotheses for ingredients origin and waste management practices were demonstrated to have a key influence on the environmental results: higher packaging recycling rates and local ingredients usage led to improved environmental results (up to 5.5%) while direct food waste disposal was responsible for slightly unfavourable performance relative to base case (below 1%). Additionally, healthier ingredients such as xylitol and fructose were used to evaluate their potential benefits from an environmental perspective. It was found that only the use of fructose was a suitable alternative sweetener for more sustainable production.

1. Introduction

The food industry is one of the most important economic sectors in Europe contributing with 14.5% to the total manufacturing turnover (European Commission, 2013). In the United Kingdom, food industry is a major economic asset with the national gross value added of 7% (Bond et al., 2013). In terms of the global environmental impact, the food supply chain contributes with 20–30% of the greenhouse gas (GHG) emissions while in the United Kingdom with 17% (European Commission, 2006; Murphy-Bokern, 2008; Del Borghi et al., 2014). This is mainly as a result of the large amount of resources required for the food production and formation of the food waste in the whole life cycle (Meneses et al., 2012; De Léis et al., 2015). In the other side, the consumers' awareness for high-quality food products produced in environmentally friendly way has increased considerably in the last decade (Notarnicola et al., 2012). In order to comply with consumers' expectations and also improve the competitiveness, companies and retailers have developed new strategic approaches for sustainable food production and consumption across the whole supply chain (Calderón et al., 2010; Notarnicola et al., 2012; Del Borghi et al., 2014). In this context, the Life Cycle Assessment (LCA) methodology has been extensively used as a tool to assess environmental profile of the food products such as meat (Reckmann et al., 2012; González-García et al., 2014, 2016), fish (Vázquez-Rowe et al., 2010), tomato (Brodt et al., 2013; Del Borghi et al., 2014), dairy (Daneshi et al., 2014; De Léis et al., 2015) and ready meals (Calderón et al., 2010).

Bakery products like breads, biscuits and cakes are consumed by 96% of the population in the United Kingdom (Foster et al., 2006). Few studies have investigated the environmental profile of breads as the most typical bakery product and found that ingredients cultivation, transportation activities and processing are the most

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* Corresponding author. Brunel University London – College of Engineering, Design and Physical Sciences, Department of Mechanical and Aerospace Engineering, Uxbridge, Middlesex, UK

E-mail address: valentina.stojceska@brunel.ac.uk (V. Stojceska).

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Abbreviations

AP	Active power (kW)
BAT	Best Available Techniques
CH_4	Methane
DEFRA	Department for Environment Food and Rural Affairs
E	Electrical energy consumption (kWh)
EPD	Environmental Product Declaration
FSA	Food Standards Agency
FU	Functional Unit
GSS	Government Statistical Service
GHG	Greenhouse Gas
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LD	Load factor
MA_n	Mass allocation percentage (%)
N_2O	Dinitrogen monoxide
oph	Operating hours (h)
P	Phosphorous
PCR	Product Category Rules
PSF	Product Sustainability Forum
R_n	Environmental results
WRAP	Waste and Resources Action Programme

Impact categories

CC	Climate Change (kg CO_{2eq})
OD	Ozone Depletion (kg CFC-11_{eq})
TA	Terrestrial Acidification (kg SO_{2eq})
FE	Freshwater eutrophication (kg P_{eq})
ME	Marine eutrophication (kg N_{eq})

important contributors to the environmental profile of breads (Andersson et al., 1994; Braschkat et al., 2003; Roy et al., 2009; Bozek et al., 2015). However, most of conventional bakery products such as biscuits and cakes have not been studied from the environmental perspective to date. There are also no studies available on the environmental performance of so called *Parnuts foods* (*Foods for Particular Nutritional purposes*) or food for specific groups. The demand for the bakery products that are gluten free (included within *Parnuts foods*) is growing rapidly as a result growing awareness and diagnosis of conditions caused by adverse reactions to wheat including wheat allergy, coeliac disease and gluten sensitivity (FSA, 2012). In this respect, the UK gluten-free market has been significantly increased and currently estimated to be worth of over £0.5 billion (FSA, 2012). The current work aims to assess environmental impacts associated with the production of gluten-free biscuits in UK following an LCA perspective. Primary inventory data from a leading manufacturer in the bakery sector was processed for this purpose. The analysis will give insight on the environmental profile of gluten-free products production, identifying both critical stages and potential improvement measures.

2. Materials and methods

The LCA methodology was applied following the ISO standards (ISO 14040, 2006; ISO 14044, 2006). The analyses were performed in compliance with the PCR CPC Group 234 (Bakery products) developed in the framework of the International EPD® System (International EPD System, 2015). The target products can be classified within class 2342 entitled “Gingerbread and the like; sweet biscuits; waffles and wafers”. Data from the biscuit production process was provided by Northumbrian Fine Foods, Ltd., which is one of the leading manufacturers for production of gluten-free biscuits, cookies and cereal bars in the UK.

2.1. Goal and scope definition

As aforementioned, the main goal of this study was to quantify the environmental performance from gluten-free biscuits production in UK. The analyses were performed following a cradle-to-grave approach, taking into account all the activities involved from the production of raw materials to the disposal of waste, in accordance with the PCR rules (International EPD System, 2015).

Three different gluten-free biscuits were assessed – named as Product 1, Product 2 and Product 3 – and the most critical stages (i.e. *hotspots*) were identified within the productive chain. Improvement actions on healthier ingredients formulations were proposed and a sensitivity analysis was performed to estimate the robustness of initial methodological criteria in agreement with the environmental results.

2.2. Functional unit (FU)

One kilogram of product at factory gate, excluding packaging material, was selected as FU for calculations and comparison between the different cases, which is in agreement with current PCR that propose “one kg of product including the relative packaging as presented to the customers (packaging weight is not included)” as the best option (International EPD System, 2015). Mass-based FUs were used in relevant research works, since the main function of food systems is food supply for human consumption (Calderón et al., 2010; González-García et al., 2014; Del Borghi et al., 2014).

2.3. System description

The system boundaries of biscuits production process include three main subsystems (Fig. 1): upstream processes (from cradle-to-gate), core processes (from gate-to-gate) and downstream processes (from gate-to-grave). The upstream processes involve the production of raw materials (including cultivation phase), other ingredients and auxiliary products together with the manufacturing of all packaging materials. During the cultivation phase, production and use inputs (i.e. seeds, agrochemicals and fossil fuels), their derived emissions (mainly direct and indirect dinitrogen monoxide emissions) and energy requirements were considered. The core processes refer to the biscuits production stages including waste treatment, cleaning operation and ingredients transportation (International EPD System, 2015). The process stages for the three biscuit products were identical as they were produced on the same production line. Finally, the downstream processes include final products transportation, use phase

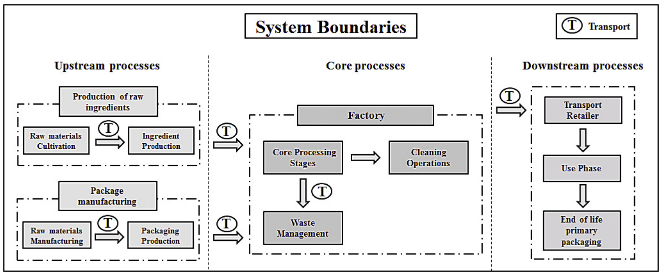

Fig. 1. Flowchart of system boundaries of biscuit production process.

and disposal of primary packaging.

The company uses modern and automated processes and equipment for gluten-free production, which is in line with the Best Available Techniques (BATs) (European Commission, 2006). Fig. 2 shows the boundaries of the plant facilities: (i) storage of raw materials, (ii) mixing and cutting, (iii) baking, (iv) cooling, (v) packaging and (vi) warehouse storage.

All the raw materials (ingredients and packaging materials) delivered to the factory are stored before being selected and used for the processing of the different products. For each type of biscuits, ingredients are mixed and blended to form the dough, which is shredded to different pieces based on the biscuit type. Once this stage is completed, the biscuits are baked in gas driven tunnel ovens then cooled and packaged. Packaging material includes tray, wrap, cardboard case and plastic film. The packaged biscuits are stored in the warehouse and distributed to the retailers.

The food manufacturers producing gluten free products have to fulfil certain criteria such as cleaning of the production process in order to avoid any cross-contamination (FSA, 2012). In this respect, the manual cleaning is carried out throughout the entire production chain using sodium chloride. Biscuit waste is generated as a by-product from the different stages of the production process: mixing, baking and cooling. The generated waste from biscuits is used for animal feed while packaging materials are recycled.

2.4. Allocation approach

Allocation can be defined as the procedure of associating the environmental burdens to each functional input or output of a multiple-function system that fulfils more than one function (ISO 14040, 2006; Suh et al., 2010). In principle, avoiding allocation is recommended by the ISO standards (ISO 14040, 2006). However, the system under evaluation can be considered as a typical multi-output (Product 1, Product 2, Product 3) system, where allocation is not avoidable. PCR guidelines for bakery products state that if allocation cannot be avoided, mass allocation must be applied (International EPD System, 2015). Consistently, mass allocation factors of 36.3%, 29.0% and 34.7% were taken into consideration for Product 1, Product 2 and Product 3, respectively. The resulting allocation percentages were calculated based on the relative contribution of each product (313 kg Product 1; 250 kg Product 2; 299 kg Product 3) to the global production (862 kg) of the entire system (Table 1).

Food waste is assumed to be a substitute for other animal feed sources, so that avoided impacts related to the production of alternative protein intakes were also included within system boundaries.

2.5. Life cycle inventory analysis and methodology development

The development of the life cycle inventory was mainly based

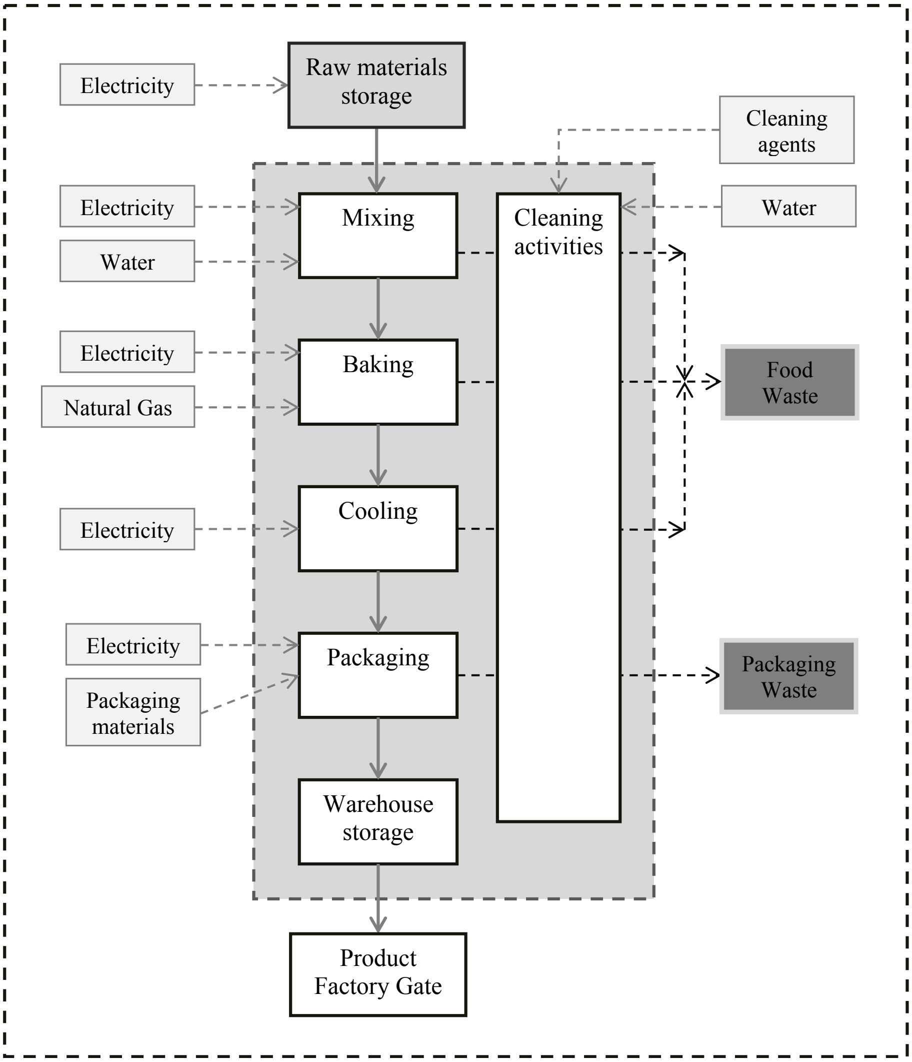

Fig. 2. Biscuit production process.

Table 1
Inventory data for the global production chain.

Inputs/Outputs	Amount	Detailed information	Data sources
Inputs from technosphere			
Raw materials [L]			
Water	218	Cleaning activities	Primary data: Biscuits company
Inputs from technosphere			
Materials [kg]			
Ingredients			
Sugar	221		Primary data: Biscuits company
Gluten free oat flour	94.0	González-García et al. (2016)	Secondary data: ecoinvent database®
Vegetable margarine	78.4	Nilsson et al. (2010)	Nemecek and Käggi (2007)
Butter	75.0		
Tapioca flour	74.8	Dalgaard et al. (2008)	
Maize flour	82.0	Dalgaard et al. (2008)	
Palm oil	56.9		
Ginger	53.9		
Soya flour	37.3		
Rice flour	32.5	Dalgaard et al. (2008)	
Gluten free oat flakes	22.2		
Water	12.9		
Salt	3.07		
Cleaning agents			
Detergent (sodium chloride)	195	Cleaning activities	Primary data: Biscuits company
Packaging			Secondary data:
Plastic	43.1	Packaging activities	Ecoinvent database®
Cardboard	147	Packaging activities	Althaus et al. (2007)
Transport [t·km]			
Road	692	Inputs & Outputs supply	Secondary data:
Sea	2049	Inputs supply	Spielmann et al. (2007)
Energy use [kWh]			
Electricity			
Storage	5.28		Primary data: Biscuits company
Mixing	15.6		Secondary data:
Baking	146		Ecoinvent database®
Cooling	385		Dones et al. (2007)
Packaging	120		
Natural gas	781	Gas Oven – Backing	
Outputs to technosphere			
Products [kg]			
Product 1	313		Primary data: Biscuits company
Product 2	250		
Product 3	299		
Waste to treatment [L/kg]			
Wastewater [L]	600	Cleaning activities	Secondary data:
Plastic	28.1	Packaging	Ecoinvent database®
Cardboard	80.9	Packaging	Hischier (2007)
Avoided products [kg]			
Plastic	15.0	Packaging	
Cardboard	66.0	Packaging	
Animal feed (avoided)	19.5	Food waste	

on primary data obtained from the target company and surveys with process engineers and operators for the period of 2014-15. The latter includes data for ingredients origin, products composition, resources consumption (energy, water and fuels), solid waste and wastewater generation and final waste management (Fig. 2). The energy use (E) of each equipment was measured using a high quality power meter (LUKE 435-II Power Quality Analyser, Fluke Industrial) and calculated using the following formula:

$$E = AP \times oph \times LF \qquad (1)$$

where: E = electrical energy consumption (kWh); AP = active power (kW); oph = operating hours (h); LF = load factor.

The inventory for the production of most ingredients, as well as cleaning agents and packaging materials, includes background data for raw materials production, chemicals use and energy requirements. The inventory data for the production of the gluten free oat flakes, gluten free oat flour and vegetable margarine were taken from published studies (McDevitt and Milá i Canals, 2011; González-García et al., 2016; Nilsson et al., 2010). Secondary data include diffuse emissions (CH_4 emissions, direct and indirect N_2O emissions) from the agrochemicals required for cereals cultivation (Althaus et al., 2007). Those data were mainly taken from ecoinvent® database (Althaus et al., 2007; Dones et al., 2007; Hischier, 2007; Nemecek and Käggi, 2007; Spielmann et al., 2007). Due to the lack of specific information, the following assumptions were made: (i) potato meal was used instead of tapioca meal, (ii) ecoinvent® processes were considered for maize meal, rice meal and potato meal with the integration of energy consumption and transport activities (Dalgaard et al., 2008).

In terms of transport activities, average distances were used for modelling the supply of the different inputs used in the production chain. According to company's data, packaging materials, cleaning agents and the majority of the ingredients were produced in the United Kingdom, whereas other ingredients, such as soya flour, tapioca flour and maize flour, were imported from Australia, Thailand and the Netherlands, respectively. The distance between ports was calculated using a web distance calculator[1] (Table 2), where lorries were considered for road transportation, while ships

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[1] www.vesseltraker.com (accessed April 2016).

for sea transportation (Calderón et al., 2010; Del Borghi et al., 2014). Similarly, average distances of 345 km for Product 2 and 355 km for Product 1 and Product 3 were assumed for the distribution by road.

Finally, during the use phase, the national scenario on waste recycling rates was considered for inventorying the end-of-life scenarios of the packaging materials (GSS, 2015). Thus, based on the UK statistics, 44.9% of packaging materials (except from wrap) is recycled, while the remaining 55.1% is disposed in landfill. Inventory data for the whole production chain are summarized in Table 1.

2.6. Impact assessment

The characterization factors of ReCiPe Midpoint (H) 1.12 (Goedkoop et al., 2013a) and the software SimaPro 8.2 (Goedkoop et al., 2013b) were used for the computational implementation of the inventories. The following environmental impact categories were assessed following the PCR guidelines (International EPD System, 2015): climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE) and marine eutrophication (ME). Due to the uncertainties on the definition of characterization factors for many active ingredients, the toxicity-related impact categories were not considered (Sleeswijk et al., 2008).

2.7. Interpretation procedure

In order to facilitate the analysis and the identification of the *hotspots*, all the processes and activities involved in the production chain were grouped in the following contributing factors: (i) storage, (ii) cleaning activities, (ii) ingredients production, (iii) mixing, baking and cooling processes, (iv) packaging, (v) transport and (vi) use.

- **Storage** includes environmental burdens from the storage of raw materials and final products prior their distribution to customers.
- **Cleaning activities** factor involves impacts from the production of cleaning agents used in the process and impacts relevant to wastewater generation and treatment.
- **Ingredients production** includes environmental burdens associated with the cultivation and manufacturing processes of ingredients used in the production line
- **Mixing, baking and cooling processes** include impacts related to the production of the energy consumed (electricity and fossil fuels).
- **Packaging** considers burdens from the production of packaging materials and the use of electricity for the packaging process.
- **Transport** factor includes emissions derived from the transport; supply of raw materials and the delivery of final products to consumers.
- **Use** phase considers emissions and discharges from product consumption. Management of packaging waste is also included, while product wastage is excluded from the system boundaries following PCR guidelines (International EPD System, 2015).
- **Avoided animal feed production** comprises the environmental credits related to the non-production of alternative animal feed sources. The use of food waste generated during mixing, baking and cooling processes replaces the use of livestock feed contributing positively to the environment.

2.8. Sensitivity analysis

Table 2
Origin and distance of ingredients supply: transport activities.

Ingredients	Origin	Distance (km)	
		Road	Sea
Sugar	United Kingdom	225	–
Oat flour	United Kingdom	337	–
Vegetable margarine	United Kingdom	274	–
Butter	United Kingdom	259	–
Tapioca flour	Thailand	451	14829
Maize flour	The Netherlands	451	237
Palm oil	United Kingdom	274	–
Ginger	United Kingdom	201	–
Soya flour	Australia	451	17616
Rice flour	United Kingdom	274	–
Salt	United Kingdom	277	–

The advantages of LCA methodology has been demonstrated on several research studies in the recent years as a tool in tracking the environmental performance of a specific product or process (Michalski, 2015). However, undeniable LCA uncertainties can lead to lack of confidence in the results (Beccali et al., 2010; Michalski, 2015). In order to handle uncertainties and avoid flawed decisions, ISO 14040 (ISO 14040, 2006) suggests the investigation of target parameters that can influence the environmental results (Baker and Lepech, 2009). The sensitivity analysis enabled the estimation of the influence of methods and data on the outcome of the current LCA study (ISO 14044, 2006).

In line with the above, a sensitivity analysis was performed with the aim of estimating to which extent initial assumptions of the present study affects the environmental results. In the baseline scenario, a recycling rate of 44.9% for the packaging materials was considered, while food waste generated from biscuits production was assumed to be valorised for livestock feed purposes. Moreover, some ingredients are provided from abroad, so that those impacts derived from their transportation were also included in the base case. In contrast, alternative approaches concerning the ingredients' origin and waste management practices were proposed and evaluated in comparison with the baseline case. The results allowed the reassessment of initial hypotheses and inventory data and contributed to the robustness of the baseline environmental results.

3. Results and discussion

3.1. Environmental impacts of gluten-free biscuits production

Table 3 reports the environmental results of the three examined products (Product 1, Product 2 and Product 3) for all impact categories in comparison with average values. The latter were calculated using the following formula:

$$\text{Average results} = \frac{ER_1 + ER_2 + ER_3}{3} \quad (2)$$

where: ER_n = environmental results for each product n relative to the different impact categories. It should be highlighted that mass allocation percentages were taken into consideration to estimate relative burdens associated with each product in relation to available inventory data in global terms.

Product 1 and Product 3 show similar environmental profile (Table 3) with values below average ratios in most impact categories (CC, OD,TA), apart from eutrophication (FE, specifically), where Product 1 accounts for higher impacts (up to 59.9%). This can be mainly due to the higher effect of oat meal production (around 94.7%; 5.77 kg P eq/kg Product 1) as one of the most important ingredients in Product 1 (Appendix, Annex I). The reason behind the impacts is directly related with the lower biomass yield reported from oat production in comparison with other crops (González-

Table 3
Environmental results (in %) of the examined products (Product 1, Product 2, Product 3) relative to average values (per FU). *Negative ratios show reductions while positive ratios indicate increase in the environmental impacts compared to the average results. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication.*

Impact categories	Units	Average values	% Relative to average values		
			Product 1	Product 2	Product 3
CC	kg CO_2 eq	**3.30**	**−26.0** 2.44	**+36.1** 4.49	**−10.2** 2.97
OD	g CFC-11 eq	**$2.97 \cdot 10^{-4}$**	**−18.0** $2.43 \cdot 10^{-4}$	**+26.3** $3.74 \cdot 10^{-4}$	**−8.28** $2.72 \cdot 10^{-4}$
TA	g SO_2 eq	**22.1**	**−21.7** 17.3	**+44.5** 32.0	**−22.8** 17.1
FE	g P eq	**3.81**	**+59.9** 6.09	**−8.80** 3.47	**−51.1** 1.86
ME	g N eq	**17.3**	**+1.67** 17.6	**+14.0** 19.7	**−15.7** 14.6

Bold value signifies $P < 0.05$.

García et al., 2016). Conversely, Product 2 exhibits higher environmental impact (apart from FE), with relative values around 36.1%, 26.3%, 44.5% and 14.0% for CC, OD, TA and ME, respectively compared to average results. Again, the production of main ingredients, including butter (above 72.1%), soybean meal (up to 16.4%) and sugar (up to 10.4%), is responsible for the unfavourable environmental performance of Product 2 compared to the other products.

However, in relative terms, analogous environmental profiles were found for the three products assessed in this study. This is evidenced by the results of Fig. 3, where the influence of the aforementioned contributing factors (in relative percentages) together with the maximum and minimum ratios for each impact category is shown. Thus, the analysis identified two critical contributing factors (in relative percentages): ingredients production and transport. Ingredients production is the main contributor for CC, TA, FE and ME (with contribution higher than 38.7%) and has an important effect on OD (over 22.2%); transport activities play also a critical role for the majority of impact categories including CC, OD and TA, with contributions ranging from 19.4% (TA) to 49.8% (OD). Emissions from the cultivation stage and fossil fuels consumption are the main responsible for these impacts, respectively. Other processes, such as packaging together with mixing, baking and cooling have also a remarkable influence on the environmental results, especially in terms of ME (up to 36.2%). In effect, according to literature, packaging is a key stage in most of food productive systems but also one of the main sources of environmental impacts and waste generation (Roy et al., 2009). In this sense, modifying current patterns towards higher recycling rates and lower packaging requirements could lead to considerable improvements to the food industry from and environmental perspective (Roy et al., 2009). On the contrary, cleaning activities and use stage have a minor impact on the environmental profile (around 3%), while storage and avoided animal feed production have a negligible effect (below 1%) in all impact categories.

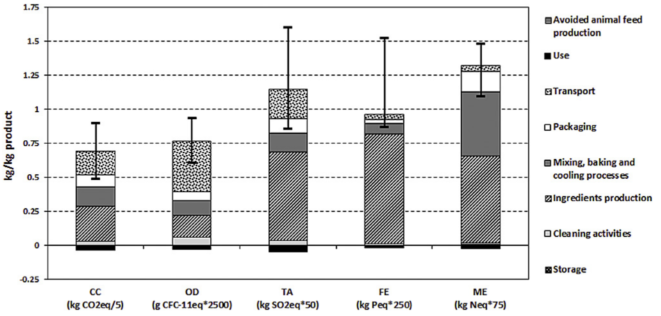

Fig. 3. Relative contributions to each impact category of the production processes considering average values. Maximum and minimum ratios are also included. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication.

These results would be in line with the published studies available in literature related to the bakery sector. Moreover, most studies revealed that the environmental profile of food systems could be enhanced with the modification of production process, packaging, distribution and/or consumption patterns (Roy et al., 2009). In this sense, alternative scenarios in the following sections were proposed in order to evaluate their potential benefits in the environmental profile of gluten-free biscuits production in the framework of the present study.

3.2. *Sensitivity analysis*

3.2.1. *Packaging waste management: alternative practices*

An alternative scenario is proposed in this section based on 100% recycling rate (Scenario A) as contrasted with base hypothesis where lower packaging rates were considered based on the national average values (GSS, 2015). Comparative results for both cases (Table 4) show that 100% recycling rate can decrease the environmental burdens for the global process, although different trend is obtained among impact categories. Thus, reduction of the impacts are more pronounced for CC, OD and TA (with ratios around 5.5%, 4.0% and 4.2%, respectively), while less significant effect is observed for FE (1.1%) and ME (1.6%). This is in agreement with the relative relevance of use phase over the environmental results (Fig. 3), where the contribution of packaging waste management is addressed. Finally, regarding the different products, the recycling rate was not significant influential factor for Product 1 (up to 2%), mainly due to less packaging requirements (without carton) for this product compared with the others (Appendix, Annex II).

3.2.2. *Food waste management: landfill disposal*

Around 15 million tonnes of food waste are produced annually in the UK out of which approximately one quarter of this type of waste is generated during manufacturing processes (Bond et al., 2013; PSF, 2013). Consumers demand high quality food products and producers respond through applying stringent product standards (Bond et al., 2013). In the case of bakery sector, main reasons for quality failure include over baking or poor appearance, among others, which could result in by products that emerge to the landfill (DEFRA, 2012). However, additional recycling and recovery options are available for segregated bakery waste. The use of formulated animal feed from this type of waste provides a potentially more sustainable strategy to improve resources efficiency (DEFRA, 2012). Thus, a comparative assessment of waste management practices (disposal and reuse) is performed in this section. The use of food

Table 4
Comparative environmental results (per FU) of the alternative scenarios proposed in relation to baseline scenario. *Negative ratios show reductions while positive ratios indicate increase in the environmental impacts compared to the baseline results. CC = climate change; OD = ozone depletion; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication.*

Impact categories	Units	Average values	% Relative to average values				
			Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
CC	kg CO_2 eq	**3.30**	**−5.45** 3.12	**+0.30** 3.31	**−0.61** 3.28	**+0.11** 3.31	**+10.5** 3.69
OD	g CFC-11 eq	**$2.97\cdot10^{-4}$**	**−4.04** $2.85\cdot10^{-4}$	**0.00** $2.97\cdot10^{-4}$	**−1.68** $2.92\cdot10^{-4}$	**−0.71** $2.94\cdot10^{-4}$	**+6.88** $3.19\cdot10^{-4}$
TA	g SO_2 eq	**22.1**	**−4.07** 21.2	**+0.45** 22.2	**−1.81** 21.7	**−4.09** 21.2	**+0.92** 22.3
FE	g P eq	**3.81**	**+1.05** 3.77	**+0.26** 3.82	**0.00** 3.81	**+1.88** 3.88	**+4.20** 3.97
ME	g N eq	**17.3**	**−1.73** 17.0	**0.00** 17.3	**−0.58** 17.2	**0.00** 17.3	**0.00** 17.3

Bold value signifies $P < 0.05$.

waste for animal feeding is considered in the baseline scenario, while an alternative practice involves the food waste disposal to landfill (Scenario B). An average value of 6.1% of protein content for food waste was considered for calculations in the baseline scenario, independently on the product under evaluation.

Table 4 shows that the disposal of food waste to landfill is accompanied by higher environmental burdens in relation to the baseline case, independently of the impact category. However, since avoided animal feed has a minor influence on the environmental results, there are no significant differences (below 1%) between the baseline scenario and Scenario B (Fig. 3). Negative effects are more pronounced for Product 1, where environmental credits related to avoided production of alternative animal feed sources show higher relevance (Appendix, Annex II).

3.2.3. Ingredients transport: alternative origin

A common practice in the food industry is to source raw materials from distant countries with low production costs (WRAP, 2011). Transportation of raw materials to the factory and of manufactured products to the market is another significant contributor to the environmental impact (Calderon et al., 2010; Roy et al., 2009). Therefore, actions to reduce the farm and food mile externalities can potentially improve the environmental performance of food production systems (Roy et al., 2009).

As already explained above, some ingredients of biscuit products are imported from overseas countries but some of those ingredients can be also produced in the UK with high potential yields (National Statistics, 2015). Accordingly, an alternative scenario considering the use of local ingredients instead of imported ones was proposed (Scenario C, Table 4). Comparative results evidenced that the selection of UK based ingredients can improve the environmental profile of the examined products; however, the reduction of the impact is lower than 3%. This can be mainly attributed to the fact that ingredients' transport represent up to 9% of the total environmental burdens associated with the transportation (Fig. 3), while the distribution of final products to clients, accounts for the highest impacts (up to 91%). Therefore, in this case, the benefits of food sold locally would have a greater favourable impact on environmental outcomes from transportation activities, in agreement with related studies in literature (Calderón et al., 2010).

3.3. Measures for the improvement of the health profile

The current work demonstrated that ingredients production constitutes the most crucial environmental factor (*hotspot*) for all the examined impact categories, independently on the considered product. More specifically, the production of fats (including butter, vegetable oil and palm oil) and sugars affected the environmental performance of the target products. Moreover, from the health perspective, excessive intake of diets rich in both fats and refined sugars can lead to several healthy problems including obesity, cardiovascular disorders or progression into neurological diseases, among others (Beilharz et al., 2014; Kearney, 2010). Consequently, more consumers become concerned about calorie content of food, with low-fat and low-sugar products growing in popularity (Aidoo et al., 2013). In this context, alternative formulations on mixtures were proposed in this study in order to evaluate their potential environmental improvements in combination with healthier products.

Thus, two additional scenarios were defined based on the partial replacement of refined sugar by alternative sweeteners: fructose (Scenario D) and xylitol (Scenario E), following the literature data provided by Isola et al. (2017) and Rettenmaier et al. (2013), respectively. The ratios of the other ingredients were also reformulated in order to preserve an adequate nutritional balance. In addition, concerning fat level, maize and rice flours were assumed to be used as main fat sources in detriment of butter, vegetable margarine and palm oil (original ingredients) in both scenarios.

According to Table 4, the use of healthier sugar sources in formulations may cause negative effects on the environmental results with higher burdens for most impact categories, mainly due to the greatest impacts during sweeteners production in comparison with conventional sugar cultivation. More specifically, the production of raw materials (mostly maize) is the main responsible of the worst performance in both cases, followed by energy requirements in terms of electricity and heat. However, much higher impacts are attributed to Scenario E compared to Scenario D (up to 11.5%). The rationale behind this difference lies in the waste management approach in both scenarios. Waste generated during the production of xylitol (Scenario E) is considered to be directly discharged to the environment (prior management procedure to comply with standards). In contrast, waste from fructose production is assumed to be used for animal feeding (in line with Isola et al., 2017), so that the environmental impacts in Scenario D are partially offset by waste valorisation, with similar results to base case. Accordingly, the use fructose as complementary source of sugar in biscuits formulations can emerge as an alternative with potential health benefits without adding more pressure on the environment.

Regarding the different products, favourable influence from the use of fructose is more significant for Product 1 and Product 2 (especially in terms of CC, OD and TA), where the use of both alternative fat and sugar sources has higher relevance. Conversely, eutrophication potential is more penalised by the increase in nitrogen and phosphorus emissions from waste management, independently of the product considered (Appendix, Annex III).

4. Conclusions

A cradle-to-grave assessment was carried out to evaluate the environmental impacts of the production of gluten-free biscuits from a leading biscuit company in the UK. The results reported that ingredients production and transport activities are the main environmental *hotspots* on the examined impact category (with contributions above 22.2% and 19.4%, respectively), in line with related studies in literature based on bakery sector. However, a sensitivity analysis revealed that an improved environmental performance (up to 5.5%) could be obtained when higher recycling rate for packaging materials is applied (up to 5.5%) as well as local ingredients are used in mixtures (by less than 3%). Accordingly, the environmental profile of the system could be enhanced by incorporating some modifications regarding distribution and/or packaging waste disposal patterns.

Moreover, alternative formulations based on the use of healthier ingredients in gluten-free products mainly focused on sugars supply were also evaluated form an environmental perspective. The use of xylitol resulted in higher environmental impacts (up to 10.5%) while the use of fructose was not damaging to the environment. This highlights the potential interest of using fructose as complementary sweetener to conventional sugar sources in the way of searching for gluten-free biscuits that are environmentally sound and safe for human health.

Nevertheless, additional alternative scenarios focusing on distribution and consumption need further investigation in order to identify their impact on the environmental profile of gluten-free biscuits production. Moreover, the research can focus on the assessment of the environmental impact resulting from the use of gluten-free ingredients within the bakery sector products as alternative to gluten-rich ingredients. The healthy benefits of the gluten-free products would be complemented by their environmental advantages.

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Appendix

1. Annex I: environmental results — ingredients production

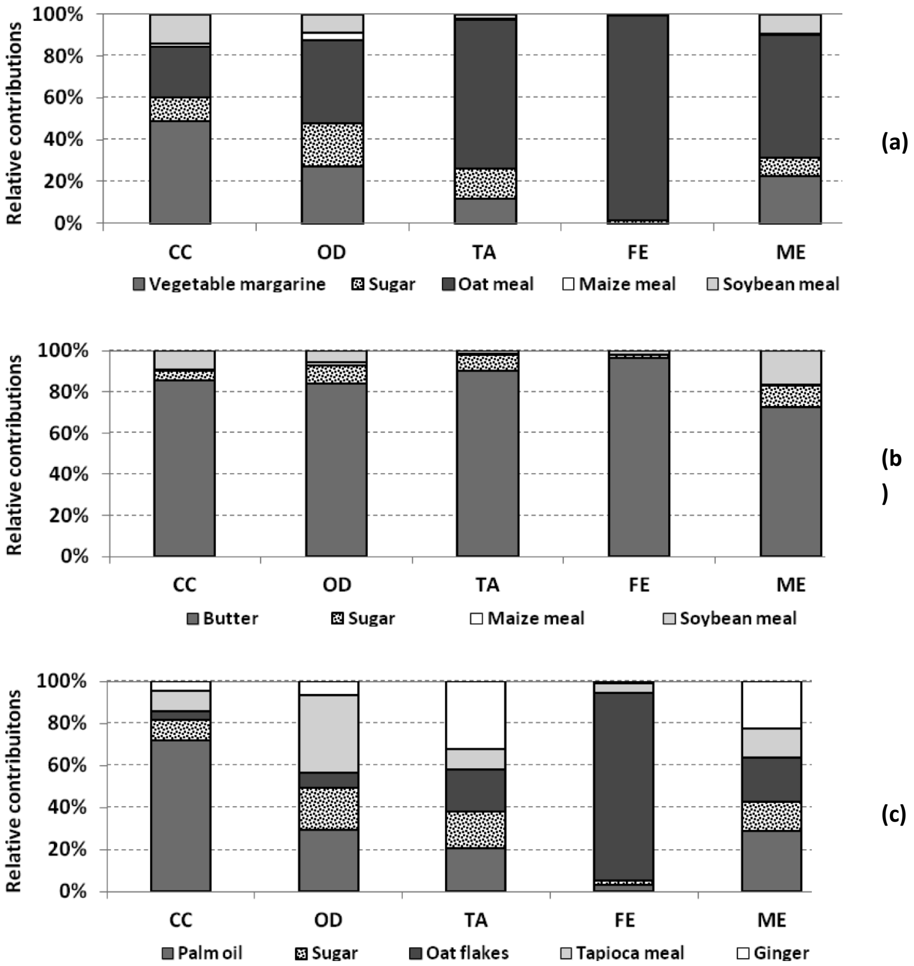

Fig. A1. Relative contributions from main ingredients used in the production of Product 1 (a), Product 2 (b), Product 3 (c).

2. Annex II: sensitivity analysis

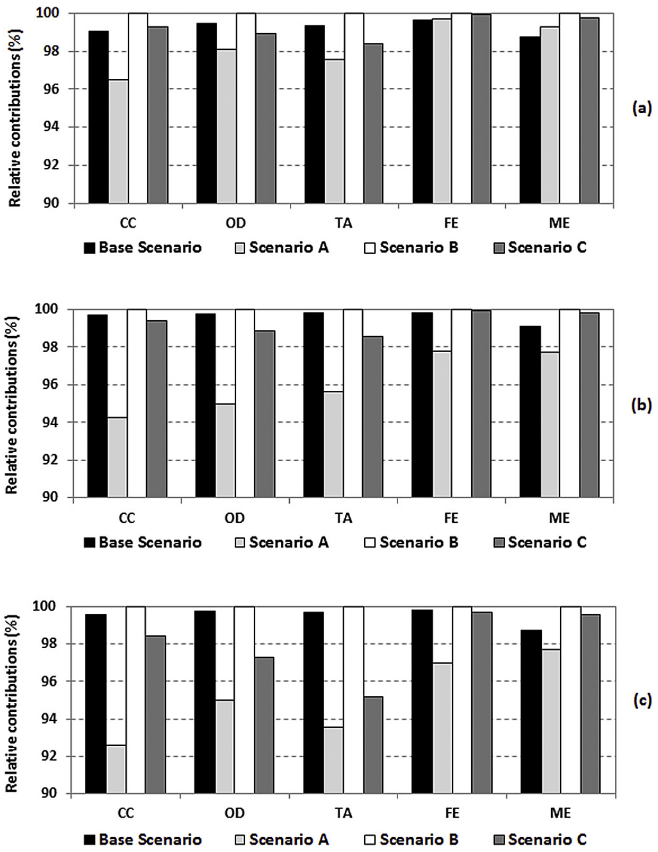

Fig. A2. Comparative environmental results considering the effects of alternative waste management practices for (Scenario A) packaging materials and (Scenario B) food waste as well as (Scenario C) alternative ingredients origin: (a) Product 1, (b) Product 2 and (c) Product 3.

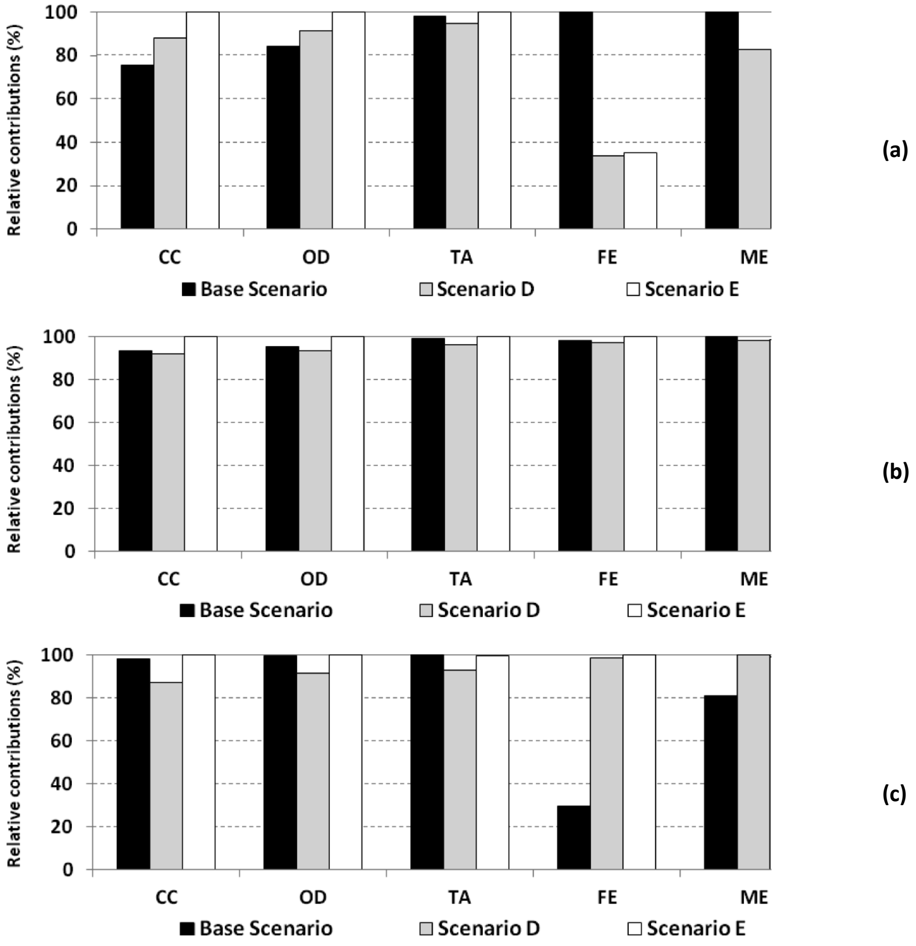

Fig. A3. Comparative environmental results considering the effects of fructose (Scenario D) and xylitol (Scenario E) as alternative sweeteners in products formulations: (a) Product 1, (b) Product 2 and (c) Product 3.

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