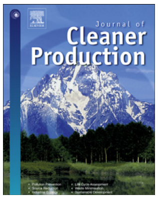
Journal of Cleaner Production 73 (2014) 294–309

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Life cycle environmental impacts of convenience food: Comparison of ready and home-made meals

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ARTICLE INFO

Article history:
Received 2 April 2013
Received in revised form
16 December 2013
Accepted 3 January 2014
Available online 13 January 2014

Keywords:
Convenience food
Home-made meals
Ready-made meals
Environmental impacts
LCA

ABSTRACT

This paper compares the life cycle environmental impacts of ready-made meals manufactured industrially with meals prepared at home from scratch. A typical roast dinner consisting of chicken meat, vegetables and tomato sauce is considered. The results suggest that the impacts of the home-made meal are lower than for the equivalent ready-made meal. For example, the global warming and human toxicity potentials are up to 35% lower and eutrophication, photochemical smog and ozone layer depletion are up to 3 times lower. The main reasons for this are the avoidance of meal manufacturing, reduced refrigeration and a lower amount of waste in the life cycle of the home-made meal. For the ready-made meal, the lowest impacts are found for the frozen meal prepared from fresh ingredients and heated at home in a microwave. The worst option for most impacts is the frozen ready-made meal with frozen ingredients that is heated in an electric oven. For the same cooking method, chilled ready-made meals have higher impacts than the frozen. The type of refrigerant used in the supply chain influences the impacts, particularly global warming and ozone layer depletion. The contribution of packaging is important for some impacts, including global warming, fossil fuel depletion and human toxicity. The main hotspots for both types of meal are the ingredients, waste and cooking method chosen by the consumer. Using organic instead of conventional ingredients leads to higher impacts. Sourcing chicken and tomatoes from Brazil and Spain, respectively, reduces environmental impacts of the meals compared to sourcing them from the UK, despite the long-distance transport. The findings of the study are used to make recommendations to producers, retailers and consumers on reducing the environmental impacts from food production and consumption.

1. Introduction

Food production and consumption exert significant pressures on the environment. For example, 29% of global emissions of greenhouse gases (GHG) are from agriculture and food production (Vermeulen et al., 2012). FAO estimate that 3.3 Gt of CO_2 eq. is emitted owing to one third of food being wasted worldwide, making food wastage the third top GHG emitter after USA and China (FAO, 2013). In the EU, food consumption accounts for 20–30% of various environmental impacts and, in the case of eutrophication, more than 50% (Tukker et al., 2006). In the UK, the food and drink sector is responsible for 14% of industrial energy consumption and 7 Mt of carbon emissions per year; it also uses 10% of all industrial water supply and produces 10% of the industrial and commercial waste stream (Defra, 2006).

Economic growth, changing dietary habits and modern lifestyles will only exacerbate environmental impacts of food in the future, particularly because of the increasing demand for meat products in developing countries such as China (USDA, 2010; OECD and FAO, 2013) as well as for convenience food in the developed world but also in China (Key Note, 2013). The convenience food sector, in particular, is expanding rapidly, with the global ready-made meals market expected to grow by 3.2% from $1.11 trillion in 2011 to $1.3 trillion in 2016. Much of this growth is expected to come from China which is the fastest growing market for ready-made meals in the world (Key Note, 2013). Currently, the US and the UK are the largest markets in the world, respectively valued at £7.2 bn (Sheely, 2008) and £2 bn (Key Note, 2013). In Western Europe, the size of the market is estimated at £3.9 bn (Sheely, 2008). The majority of this is due to the UK market, which is expected to grow by 20% by 2017 (Key Note, 2013).

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0959-6526
http://dx.doi.org/10.1016/j.jclepro.2014.01.008

Convenience food now constitutes more than a third of the British food market with approximately 8.8 kg of chilled and frozen ready-made meals consumed per capita per year (Millstone and Lang, 2008). This makes Britons the largest consumer of ready-made meals in Europe and the second largest worldwide (after the US); they are also the largest consumers of chilled ready-made in the world (Key Note, 2013). Even meals that have traditionally been prepared at home are gradually being replaced by ready-made meals – now one in four Britons eats ready-made Christmas dinner (MINTEL, 2011). Yet, there is currently scant information on the life cycle environmental impacts of convenience food, and particularly ready-made meals. Whilst numerous life cycle assessment (LCA) studies of single food items have been carried out, there are few studies of complete meals with most focussing on global warming potential (e.g. Carlsson-Kanyama, 1998; Wiltshire et al., 2008; Stichnothe et al., 2008; Espinoza-Orias et al., 2010) or on a limited number of environmental impacts such as acidification, eutrophication and energy consumption (e.g. Sonesson et al., 2005; Davis and Sonesson, 2008; Davis et al., 2010; Berlin and Sund, 2010; Saarinen et al., 2010; 2012). To date, only two studies have considered a broader range of LCA impacts of ready-made meals, both based in Spain: Calderón et al. (2010) looked at a canned ready-made meal with pork meat and pulses while Zufia and Arana (2008) evaluated a dish with cooked tuna and tomato. In an attempt to contribute towards further understanding of environmental impacts of the convenience food sector, this paper considers one of the most popular ready-made meals in the UK – roast dinner – consisting of roast chicken, vegetables and an accompanying sauce. The environmental impacts are compared to the same meal prepared at home. A range of different scenarios is examined for both types of meal to explore the influence of different factors on the impacts. Although the study is based in the UK, the findings and recommendations for improvements are generic enough to be applicable elsewhere and to other similar types of meals.

2. Methodology

LCA has been used as a tool to estimate the environmental impacts of both the ready and home-made meals, following the ISO 14040/14044 methodology (ISO, 2006a & b). The methodology, data and the assumptions are described in more detail in the following sections.

2.1. Goal and scope of the study

The main goal of this study is to evaluate the environmental impacts of a ready-made meal prepared industrially and compare it to the impacts from an equivalent meal made at home. A further goal is to analyse the influence on the impacts of different factors such as ingredient sourcing, refrigeration and home-cooking options. The results of the study are aimed at both food producers and consumers.

The functional unit is defined as 'preparation and consumption of a meal for one person'. The weight of the meal is 360 g and it consists of roast chicken and three vegetables – potatoes, carrots and peas – served with tomato sauce. This meal has been chosen for study as it represents a typical British 'roast dinner'. The meal is consumed at home. The scope is from 'cradle to grave' and the study is based in the UK.

2.2. System definition and system boundaries

Fig. 1 outlines the life cycles of the ready-made and the meal prepared at home; the individual steps involved in each stage are defined in Table 1. As shown, the life cycle of the ready-made meal involves chicken rearing and cultivation of the vegetables, their processing in a slaughterhouse and at a regional distribution centre (RDC), respectively, preparation of the meal in a factory, its subsequent transport to another RDC, retailer and finally to consumer's home where it is prepared according to manufacturer's instructions. The life cycle of the home-made meal is similar, except that the meal is fully prepared at home, starting from the fresh ingredients.

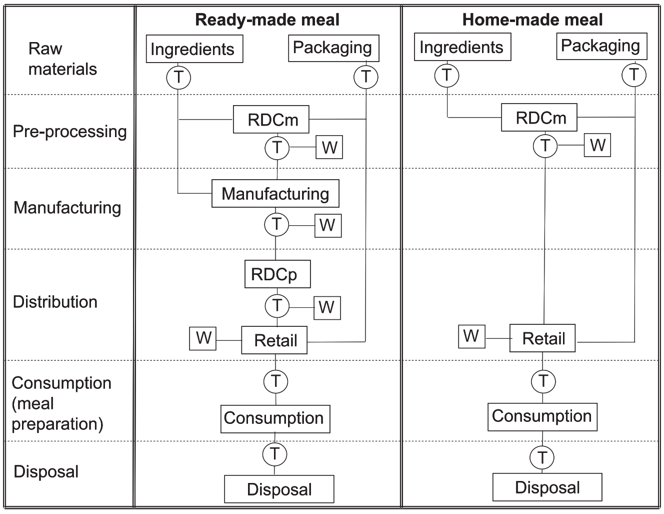


Fig. 1. Life cycles of the ready and home-made meals. [RDCm and RDCp: Regional distribution centre for raw materials and products, respectively; T-transport; W-waste].

2.2.1. Raw materials (ingredients)

As shown in Table 2, the ingredients used for both meals are chicken meat, potatoes, carrots, peas, tomato sauce, salt and oil. All the ingredients are assumed to be produced in the UK, apart from the tomato paste used for the tomato sauce, the majority of which is imported to the UK from Spain (FAO, 2009). In one of the scenarios discussed later, chicken is also assumed to be imported from Brazil (Defra, 2008a; BPEX, 2013).

This stage involves chicken rearing and cultivation of the vegetables. The latter are transported from the farm to the RDCm to be processed while the chicken is processed in the slaughterhouse and transported directly to the meal manufacturer. The tomato paste, oil and salt are also transported directly from their respective manufacturers to the meal producer.

2.2.2. Pre-processing

Pre-processing includes processing the vegetables and slaughtering the chickens, packing and either chilled or frozen storage. The data assumed for this stage are given in Table 3.

The vegetables are processed at RDCm including sorting, peeling, washing and cutting. For frozen ready-made meals, blanching and fast cooling of vegetables is also carried out. Chilled vegetables are packaged in plastic crates and transported by refrigerated trucks to the meal manufacturer. Frozen vegetables are packaged in plastic bags and cardboard boxes and transported to the manufacturer by freezer-trucks. Water used for pre-processing the vegetables is collected and treated (EC, 2006). The waste, including the peel and spoilage, is assumed to be landfilled (see Table 4). However, using the waste for animal feed instead of landfilling is also considered within the sensitivity analysis later in the paper.

Table 1
Stages considered in the life cycle of the ready and home-made meals.

Stage	Ready-made meal	Home-made meal
Raw materials (ingredients)	Cultivation of vegetables and tomatoes	Cultivation of vegetables and tomatoes
	Chicken rearing	Chicken rearing
	Manufacture of tomato paste	–
	Manufacture of packaging	Manufacture of packaging
	Waste management	Waste management
	Transport to RDCm[a]	Transport to RDCm
Pre-processing of ingredients	Processing of vegetables at RDCm	Processing of vegetables at RDCm
	Slaughtering, processing and storage of chicken meat	Slaughtering, processing and storage of chicken meat
	Packing	Packing
	Waste management	Waste management
	Transport to manufacturer	–
Manufacture of meal	Meal manufacturing	–
	Packing	–
	Waste management and water treatment	–
	Chilled or frozen storage	–
	Transport to RDCp[b]	–
Distribution	Chilled or frozen storage at RDCp	–
	Transport to retailer	Transport to retailer
	Chilled or frozen storage at retailer	Chilled storage at retailer
	Waste management	Waste management
	Packaging (shopping bags)	Packaging (shopping bags)
Consumption (meal preparation)	Transport of the meal from retailer to consumer's home	Transport of the ingredients from retailer to consumer's home
	Refrigerated storage at home	Refrigerated storage at home
	Cooking of the meal (oven or microwave)	Cooking of the meal (chicken roasting, vegetables boiling, tomato sauce cooking)
Final disposal of waste	Waste transport and management (packaging and food waste)	Waste transport and management (packaging and food waste)

[a] RDCm – Regional distribution centre for raw materials (vegetables).

[b] RDCp – Regional distribution centre for products (ready-made meal).

The chicken meat is processed in a slaughterhouse (Nielsen et al., 2003), where it is packaged and stored ready to be delivered to the retailer. Chicken waste (offcuts and carcass) are used for bone-meal production.

2.2.3. Manufacture

This stage involves cooking of the ready-made meal (from fresh or frozen ingredients), its packing and either chilled or frozen transportation to the RDCp. Vegetables and tomato sauce are cooked together while the chicken meat is cooked separately. The cooked ingredients are then combined, packaged and refrigerated or frozen. The utilities used in the manufacturing process are listed in Table 5.

2.2.4. Distribution

The ready-made meals are first stored at the RDCp and then distributed to the retailer in refrigerated or freezer-trucks while the ingredients for the home-made meal are distributed directly from RDCm to retailer in refrigerated trucks. The ready-made meals and the ingredients for the home-made meal are then transported by the consumer for consumption at home. The data used for this stage are specified in Table 6.

Table 2
Composition of the ready and home-made meal as served.

Ingredients	Weight (g)	Contribution (%)
Chicken	98	27.22
Potatoes	87.5	24.31
Carrots	35	9.72
Peas	35	9.72
Tomato sauce	94.5	26.25
Tomato paste	*66.2*	*70*
Onions	*28.3*	*30*
Salt	1	0.28
Vegetable oil	9	2.50
Total	360	100

2.2.5. Consumption

This stage includes storage and meal preparation at home. The ready-made meal can be cooked in a microwave or a conventional oven. The assumptions for storage and preparation of the ready-made meal are listed in Table 7. Note that refrigerated storage

Table 3
Storage times, utilities and refrigerant used in the pre-processing stage.

	Processing[a] (amount per meal)	RDCm[b] (amount per meal)
Chilled raw materials		
Storage time (hr)	–	12
Electricity (Wh)	5.8	0.0778
Water (l)	1.127	–
Steam (Wh)	0.3	–
Refrigerant (ammonia) charge (mg)	–	180.5
Refrigerant (ammonia) leakage (mg)[c]	–	27.1
Frozen raw materials		
Storage time (hr)	–	158
Electricity (Wh)	5.9	0.739
Steam (Wh)	0.4	–
Water (l)	2.43	–
Refrigerant (ammonia) charge (mg)	–	211
Refrigerant (ammonia) leakage (mg)[c]	–	31.7

[a] Data source: EC (2006).

[b] Data source: Brunel University (2008).

[c] Assuming walk-in chillers/freezers in RDCm, refrigerant leakage rate is 15% (Brunel University, 2008).

Table 4
Assumptions for waste.

Stage	Waste	Reference
Pre-processing	15% of chilled ingredients[a]	Milà i Canals et al. (2008), EC (2006),
	17% of frozen ingredients[b]	Brunel University (2008)
	27% of whole chicken	Nielsen and Pontoppidan (2003)
Manufacture	16% of ingredients	BIS (2011)
	0.65% of final product	BIS (2011)
RDCp and retail	2% for chilled and 1% for frozen	Brunel University (2008)
Consumption	18% of vegetables and 8% of meat & tomato paste for preparation of home-made meal	WRAP (2009)
	24% of the ready and home-made meals as post-consumer waste	WRAP (2009)

[a] 13% for pre-processing, including the peel and spoilage, and 2% from chilled storage.
[b] 11% from raw materials to frozen (including the peel and spoilage), 5% from frozen to packaged and 1% during frozen storage.

Table 6
Storage times, utilities and refrigerant used in the RDCp and at retailer.

	RDCp[a] (amount per meal)	Retailer[b] (amount per meal)
Chilled ready-made meal		
Storage time (hr)	12	48
Electricity (Wh)	0.0463	52.8
Refrigerant (R134a) charge (mg)	–	150.7
Refrigerant (R134a) leakage (mg)	–	22.6
Refrigerant (ammonia) charge (mg)	180.8	–
Refrigerant (ammonia) leakage (mg)	27.1	–
Frozen ready-made meal		
Storage time (hr)	158	120
Electricity (Wh)	0.61	136.8
Refrigerant (R134a) charge (mg)	–	47.76
Refrigerant (R134a) leakage (mg)	–	7.16
Refrigerant (ammonia) charge (mg)	314.5	–
Refrigerant (ammonia) leakage (mg)	47.2	–
Chilled ingredients for the home-made meal		
Storage time for chicken meat (hr)	–	48
Storage time for vegetables (hr)	–	72
Electricity chicken (Wh)	–	4.5
Electricity vegetables (Wh)	–	10
Refrigerant (R134a) charge (mg)	–	36.25
Refrigerant (R134a) leakage (mg)	–	5.44

[a] Data source: Brunel University (2008).
[b] Medium-size supermarket (floor area 1400 m^2); includes consumption of energy for chilled and frozen storage, lighting and heating, ventilation and air conditioning. Data source: Brunel University (2008).

considers the electricity used but no refrigerant leakage as this is negligible for domestic refrigerators and freezers.

As mentioned earlier, the home-made meal is made from fresh ingredients with the chicken roasted in an electric oven and the vegetables cooked on an electric hob or in a microwave (see Table 8). The tomato sauce can be prepared either from a tomato paste or from scratch. The amount of paste and tomatoes needed in each case are shown in Table 9, together with the amount of tomato sauce used in the ready-made meal, for comparison. Note that the total amount of tomato sauce given in Table 9 is slightly different for the home and ready-made meals owing to the different amount of waste in the two systems: 8% for the home-made sauce and 16% for manufacturing the ready-made sauce (see Table 4). This is also the reason why the amount of ready-made sauce appears to be higher (76.7 g per meal) than the amount given in Table 2 (66 g) as the former represents the total amount required before the waste is taken into account.

Water consumption is also considered in the study. For the home-made meal, a total of 4.5 l is assumed to be used (Defra, 2008 b&c) for washing the ingredients, boiling the vegetables and washing up the dishes by hand. It is also assumed that boiling the vegetables on the hob needs 525 ml of water, while using the microwave requires only 31.5 ml (Defra, 2008c). For the ready-made meal, water is only used for washing up so that the total water consumption is 1 l (Defra, 2008 b&c).

2.2.6. Disposal

This stage considers only the waste generated in the consumption stage; the waste from the other life cycle stages is considered within each stage. The assumptions for post-consumer waste are summarised in Table 4. All the waste and packaging, including the shopping bag, are assumed to be landfilled. These assumptions are in accordance with the prevalent UK waste management practice for food-related products and packaging (Defra, 2011).

Table 5
Storage time, utilities and refrigerant used in the manufacturing stage.

	Amount per meal[a]
Storage time (hr)	12
Fuel oil (l)	0.0397
Electricity (kWh)	0.326
Water (l)	4.285
Refrigerant (R22) charge (mg)	76
Refrigerant (R22) leakage (mg)	11.4[b]

[a] Data source: meal manufacturer.
[b] Data source: Brunel University (2008).

2.2.7. Packaging

All the primary, secondary and tertiary packaging has been considered, including the ingredients and ready-made meal packaging, shopping bags, crates, boxes, drums and pallets. The packaging data are summarised in Table 10 and Table 11.

2.2.8. Transport

The transport assumptions are summarised in Table 12. All road transport is by diesel vehicles, assuming an empty return trip. The exception to this is consumer's car which is run on petrol. The chicken imported from Brazil (used in one of the scenarios discussed later in the paper) is shipped to the UK by a bulk carrier. Refrigerated or frozen transport is considered as appropriate and the assumptions for the refrigerant are given in Table 13.

2.3. Data sources

The data sources are summarised in Table 14. As shown, most data for the ingredients correspond to their country of origin considered in this study. The exceptions are the data for carrots and onions which are not available for the UK so that Danish data have been used instead (Nielsen et al., 2003). Furthermore, data for peas are also not available so that proxy data for green beans have been used following recommendations by Milà i Canals et al. (2011) on dealing with data gaps in the food sector. No data were available for organic onions and peas so that only conventional produce is considered in the organic version of the meal.

As also indicated in Table 14, the LCA data for wastewater treatment and waste management sourced from Ecoinvent (2009) are for the Swiss conditions as the inventory data for UK are not available.

Table 7
Storage at home and cooking assumptions for the ready-made meal.

Storage	Storage (days)	Electricity consumption for storage[a] (Wh/meal)	Cooking option	Cooking specification	Cooking time[b] (min)	Energy consumption for cooking[c] (Wh/meal)
Chilled	0.5	2	Microwave	750 W	6.5	78.6
Frozen	2	18		800 W	9	391.5
Chilled	0.5	2	Oven (electric)	200 °C	25	1270
Frozen	2	18		200 °C	40	2033

[a] Estimated based on Nielsen et al. (2003), assuming the volume of the product of 750 cm^3 and half empty fridge or freezer.

[b] Based on manufacturer instructions.

[c] Estimated based on average electricity consumption by microwaves of 0.0435 MJ/min and by electric ovens of 0.183 MJ/min (Jungbluth, 1997). For sensitivity analysis, gas ovens are used assuming energy consumption of 0.12 MJ/min (Jungbluth, 1997).

2.4. *Allocation*

Allocation was necessary in the manufacturing stage since several products are produced in the same factory and only annual operational data have been available from the manufacturer. The allocation has been carried out on a mass basis, related to the total annual production of the ready-made meals considered here, relative to the total production in the factory. Economic allocation was not possible owing to the confidentiality of cost data. Mass allocation was also used in the pre-processing and distribution stages to allocate the utilities and refrigerant use as well as between the chicken meat and bone meal. System expansion was used to credit the system for using vegetable waste from pre-processing to displace animal feed, an option considered within the sensitivity analysis.

2.5. *Scenarios*

To examine the influence of different parameters on the environmental impacts, several scenarios have been developed for the ready and home made-meals. As shown in Table 15, the ready-made meal scenarios RM-1 to RM-8 assume that the ingredients are sourced from conventional farms in the UK, except for the tomato paste, which is imported from Spain (FAO, 2009). The difference between these scenarios is that they consider either fresh or frozen ingredients; fresh or frozen meal; and meal cooking at home in a microwave or an electric oven. The remaining three ready-made meal scenarios (RM-9 to RM-11) consider respectively the effect of ingredient sourcing by substituting the British chicken with the Brazilian, Spanish with the British tomatoes for the tomato sauce, and conventional with organic ingredients. The reason for considering the Brazilian chicken in particular is that Brazil is the largest chicken-meat exporter worldwide (FAOstat, 2013) and the fourth exporter of processed chicken meat to the UK with 21,456 tonnes exported in 2012 (BPEX, 2013). Regarding the tomato sauce, although the majority of tomato paste used for the sauce is imported into the UK from Spain (FAO, 2009), scenario RM-10 explores how the impacts change if domestic tomatoes are used instead. Finally, organic ingredients are considered as there is a growing market for organic produce in the UK (Soil Association, 2013) which is gradually starting to be reflected in the ready-meals market (Key Note, 2013). The data sources for these scenario are summarised in Table 14. Note that in the meal with the organic ingredients, peas and onions are from conventional farms owing to a lack of data for organic production.

Four scenarios are considered for the home-made meal (Table 16). Scenario HM-1 is similar to RM-1, assuming that all the ingredients are sourced from conventional farms and that they are cooked fresh with the chicken roasted in an electric oven and the vegetables and tomato sauce prepared on an electric hob; the tomato sauce is made from the Spanish ready-made tomato paste. HM-3 is exactly the same and HM-1, except that the vegetables and tomato sauce are cooked in a microwave. On the other hand, HM-2 assumes the use of all-British organic ingredients and preparation of tomato sauce from fresh tomatoes. The fourth, HM-4, scenario is the same as HM-1 but here the British chicken is replaced by the Brazilian.

3. Results and discussion

This section first presents the environmental impacts of the ready-made meal for different scenarios. This is followed by an equivalent discussion for the home-made meal in Section 3.2. Next, the environmental impacts of the two types of meal for different scenarios are compared and discussed in Section 3.3. Finally, in Section 3.4, a sensitivity analysis is performed to examine the influence of some further parameters on the impacts of the two types of meal. The impacts have been estimated according to the CML 2011 method (Guinée et al., 2002) using Gabi LCA software V4.4 (PE International, 2011).

3.1. *Ready-made meal*

The environmental impacts of the ready-made meal for different scenarios are presented in Fig. 2–4. The results comparing the influence of different refrigeration and cooking options (scenarios RM-1 to RM-8 and RM-11) indicate that the best option for most impacts is scenario RM-3, which corresponds to the frozen

Table 8
Storage at home and cooking assumptions for the home-made meal.

Ingredients	Refrigerated storage (days)	Cooking option	Cooking specification	Cooking time (min)	Energy consumption for cooking (Wh)[a]
Roast chicken	0.5	Oven (electric)	200 °C	10	508
Tomatoes/tomato sauce	–	Hob (electric)	–	7	158
	–	Microwave	700 W	5	85
Vegetables	0.5	Hob (electric)	–	15	474
		Microwave	700 W	6.5	78.9

[a] Estimated based on average electricity consumption by electric hobs of 0.114 MJ/min and electric ovens of 0.183 MJ/min (Jungbluth, 1997). For sensitivity analysis, gas hob and oven are used, assuming average energy consumption of 0.108 MJ/min and 0.12 MJ/min, respectively (Jungbluth, 1997).

Table 9
Tomato sauce for the home and ready-made meals.

Meal type	Amount (g/meal)
Home-made meal: tomato sauce from tomato paste	
Tomato paste	47.6
Water	23.8
Home-made meal: tomato sauce from fresh tomatoes	
Fresh tomatoes	132.3
Ready-made meal: tomato sauce prepared in a factory	
Tomato paste	51.1
Water	25.6

Table 11
Packaging for tomato paste.

Packaging specification	Can[a]	Drum[b]	Bag[b]
Material			
Tinplate (kg)	0.065	–	–
Glass (kg)	–	–	–
Stainless steel (kg)	–	27.13	–
Low-density polyethylene (kg)	–	–	0.5
Units per box (number)	24	–	–
Units per pallet (number)	80	4	16

[a] The can contains 400 g of tomato paste.
[b] Data source: FAO (2009) and EC (2006).

meal made with fresh (chilled) conventionally-farmed ingredients and cooked in a microwave (Fig. 2). The effect on the impacts of ingredient sourcing (RM-9 and RM-10) is mixed. These results are discussed in more detail below.

3.1.1. Influence of refrigeration and cooking (scenarios RM-1 to RM-8)

3.1.1.1. Global warming potential (GWP). As shown in Fig. 2a, the lowest GWP of 2.4 kg CO_2 eq./meal is estimated for the frozen microwaved meal (RM-3 and RM-7). The highest impact of 3.6 kg CO_2 eq. is found for the oven-cooked meal, regardless of whether the ingredients or the meal are fresh or frozen (RM-2, RM-4, RM-6 and RM-8). Therefore, cooking of the meal at home is the most important differentiating factor for the GWP of the considered ready-made meal with the GWP of oven-cooking the frozen meal (RM-4 and RM-8) being 6.5 times higher than microwaving the chilled meal (RM-1 and RM-5). Another differentiator, although to a smaller extent than cooking, is whether the meal is chilled or frozen with the former having a 15% higher GWP (2.9 g CO_2 eq. for RM-5) than the latter (2.4 kg CO_2 eq. for RM-3 and RM-7) for the same cooking method at home. This is due to the higher usage and leakage of refrigerants during storage of the chilled meal at retailer (see Table 6) because they are kept in open refrigerators while frozen meals are stored in closed display cabinets. Hence, despite much longer storage times of the frozen meals, the refrigerant consumption and leakage are much higher for the chilled meals, leading to a higher GWP. A further reason is the higher amount of waste in the chilled chain compared to the frozen (see Table 4).

The main contributor to the GWP across all the scenarios are the ingredients contributing on average 42% (Fig. 2a). As illustrated by the example of RM-1 in Fig. 3, among the ingredients, chicken contributes the majority of GWP (82%), mainly from the chicken feed and the chicken manure. The next largest contributor is the tomato paste (9%), largely because of its manufacture and transport to the UK from Spain. The total contribution of the vegetables is small (6%).

3.1.1.2. Abiotic depletion potential (ADP). The results for the depletion of elements and fossil resources are presented in Fig. 2b&c.

ADP$_{elements}$: There is little difference between the scenarios for this impact which ranges from 5.0 to 5.2 g Sb eq./meal with the frozen meals being slightly better than the chilled. This is because there is more waste in the supply chain of the chilled meal (Table 4) requiring overall a higher amount of raw materials, which contribute the large majority (>99%) to the depletion of elements (see Fig. 2b). However, the results for this impact should be treated with caution throughout the paper owing to limited data availability for the ADP$_{elements}$ for some of the ingredients.

ADP$_{fossil}$: A similar trend is noticed for fossil fuel depletion as for the GWP but the lowest value (16.5 MJ/meal) is now found for the chilled meal RM-1 and the highest for the frozen RM-8 (34 MJ). However, the contribution of the life cycle stages is slightly different compared to the GWP: here, the consumption contributes on average 36%, followed by the meal manufacture (26%). Packaging and distribution add further 16% and 8%, respectively. Unlike the GWP, the contribution of raw materials is small (8%) as is that from pre-processing (5%) and disposal (1%).

3.1.1.3. Acidification potential (AP). The lowest AP is for RM-7 (45.3 g SO_2 eq./meal) and the highest for RM-4 (49.6 g SO_2 eq./meal). This impact is also mainly from the raw materials which contribute around 90% across all the scenarios (Fig. 2d). This is due to the fertilisers and pesticides used for the cultivation of vegetables as well as the chicken feed and manure. The rest of the impact is contributed by the consumption stage (5%) and meal manufacture (2.6%), with the remaining stages contributing less than 2% each. The main difference for this impact between the different

Table 10
Packaging for the ready-made meal.

Packaging specification	Meal packaging[a]	Crate[b]	Box[c]	Euro pallet[d]	Shopping bag[e]
Material					
Polyethylene film (kg)	0.01	–	–	–	–
Polyethylene terephthalate (kg)	0.025	–	–	–	–
Cardboard (kg)	0.015	–	0.365	–	–
Polypropylene (kg)	–	2.8	–	–	–
Low-density polyethylene (kg)	–	–	–	–	0.01
Wood (kg)	–	–	–	21	–
Weight per unit (kg)	–	20	8	750–1000	4.5
Units per pallet (number)	–	32	70	–	–
Re-use rate (number)	–	1000	–	1000	–

[a] Data source: Meal manufacturer.
[b] Data source: Brunel University (2008) and Solent Plastic (2013). Crate volume: 26.5 l.
[c] Data source: Brunel University (2008) and Packaging Calculator (2013).
[d] Data source: Brunel University (2008) and Fox's Pallets (2013).
[e] Data source: Brunel University (2008).

Table 12
Transport distances.

Stage	Country of origin	Distance and transportation mode	Vehicle[a]
To farm			
Fertilizer, pesticides, etc.	UK	100 km by road	Truck, 7.5–16 t
From farm to RDCm/slaughterhouse			
All ingredients[a]	UK	200 km by road	Truck, 32 t
Tomato paste	Spain	1300 km by road to the UK	Truck, 32 t
Chicken	Brazil[b]	10,000 km by sea to the UK	Transoceanic freight ship
		400 km by road from Brazilian farm to harbour and from UK harbour to meal manufacturer or retailer	Truck, 32 t
From RDCm/slaughterhouse to manufacturer or retailer	UK	100 km by road	Truck, 32 t
From manufacturer to RDCp[c]	UK	100 km by road	Truck, 32 t
From RDCp to retailer[c]	UK	100 km by road	Truck, 32 t
From retailer to consumer's home[d]	UK	7.5 km by road	Petrol car
From consumer's home to waste treatment[d]	UK	25 km by road	Articulated lorry, 21 t

[a] All truck types assumed to be Euro 5.
[b] Considered in one of the scenarios.
[c] Data on refrigerated transport from Brunel University (2006).
[d] Assumption based on Pretty et al. (2005).

Table 13
Refrigerant used for refrigerated transport.

	Chilled (mg/meal)	Frozen (mg/meal)
Refrigerant charge (R134a)	5.77	6.35
Refrigerant leakage	1.36	1.5

[a] Trucks operate 250 days/yr for 10 h/day. The average leakage rate: 23.6%. Data source: Brunel University (2008).

scenarios is related to the preparation of the meal, with oven cooking of the frozen meal having around 8% higher total AP than for the microwaved meal; the equivalent difference in the options for the chilled meal is 5%.

3.1.1.4. Eutrophication potential (EP). Similar to the $ADP_{elements}$, there is little difference in this impact between the eight scenarios considered. It ranges between 15.3 g PO_4 eq./meal for RM-3 and 16.2 g PO_4 eq. for RM-6, suggesting that neither the fresh or frozen

Table 14
Overview of sources of life cycle inventory data used in the study.

Stage	Detail	Life cycle inventory data	Data specific to country
Raw materials	British conventional & organic chicken	Williams et al. (2006)	UK
	Brazilian conventional chicken	Da Silva et al. (2010)	Brazil
	British conventional & organic tomatoes	Williams et al. (2006)	UK
	Spanish conventional tomatoes	Anton et al. (2005)	Spain
	British conventional & organic carrots	Nielsen et al. (2003)	Denmark
	British conventional onions	Nielsen et al. (2003)	Denmark
	British conventional peas[a]	Milà i Canals et al. (2008)	UK
	Tomato paste	EC (2006); FAO (2009)	Spain
	Slaughterhouse	Nielsen et al. (2003)	Denmark
	Polypropylene crate	Brunel University (2008)	UK
	Shopping bags	Brunel University (2008)	UK
	Cardboard box	Brunel University (2008)	UK
	Pallet	Brunel University (2008)	UK
RDCm	Fresh pre-processing	Brunel University (2008); EC (2006)	UK
	Frozen pre-processing	Brunel University (2008); EC (2006)	UK
Manufacturing	Ready-made meal	UK manufacturer 2010[b]	UK
	Emissions from food manufacture	EC (2006)	EU
RDCp	Energy consumption	Brunel University (2008)	UK
Retail	Supermarket details	Brunel University (2008)	UK
Consumption (meal preparation)	Microwave and oven electricity; water consumption	Jungbluth (1997); Defra (2008b&c); Ecoinvent (2009)	UK
Wastewater	Waste treatment sewage	Ecoinvent (2009)	CH
Waste management	Food landfilling	Ecoinvent (2009)	CH
	Landfill of cardboard, packaging	Ecoinvent (2009)	CH
	Landfill of wood	Ecoinvent (2009)	CH
	Landfill of plastics (PP, HDPE)	Ecoinvent (2009)	CH
	Landfill of metal (tin)	Ecoinvent (2009)	CH
Transport	Road transport (diesel vehicles)	Ecoinvent (2009)	EU
	Bulk sea carrier	Ecoinvent (2009)	EU
	Refrigerated transport	Brunel University (2008)	EU

[a] Green beans used as proxy owing to a lack of data.
[b] Confidential.

Table 15
Scenarios for the ready-made meal.

Scenario	Raw materials	Pre-processing	Manufacture & distribution	Consumption (meal preparation)
RM-1	Chicken & vegetables: British, conventional Tomato paste: Spanish tomatoes, conventional	Fresh (chilled)	Fresh (chilled)	Microwave
RM-2	As RM-1	Fresh (chilled)	Fresh (chilled)	Oven
RM-3	As RM-1	Fresh (chilled)	Frozen	Microwave
RM-4	As RM-1	Fresh (chilled)	Frozen	Oven
RM-5	As RM-1	Frozen	Fresh (chilled)	Microwave
RM-6	As RM-1	Frozen	Fresh (chilled)	Oven
RM-7	As RM-1	Frozen	Frozen	Microwave
RM-8	As RM-1	Frozen	Frozen	Oven
RM-9	Chicken: Brazilian, conventional All other ingredients: as in RM-1	As RM-1	As RM-1	As RM-1
RM-10	Tomato paste: British tomatoes, conventional All other ingredients: as in RM-1	As RM-1	As RM-1	As RM-1
RM-11	Chicken, carrots, potatoes: British, organic All other ingredients: as in RM-1	As RM-1	As RM-1	As RM-1

options nor the different cooking methods influence this impact significantly (see Fig. 2e). The main contribution is from the raw materials (~74%), mainly due to the agricultural stage, particularly from fertilisers and chicken manure. The other two significant stages are post-consumer waste disposal (~10%), mainly because of the landfilling of the waste food and packaging. Pre-processing and manufacture contribute 7% and 5%, respectively; the contribution of the remaining stages is small (<2%).

3.1.1.5. Freshwater aquatic ecotoxicity potential (FAETP). As shown in Fig. 2f, the lowest FAETP of 602.3 g DCB eq./meal is found for RM-3 and the highest for RM-6, equal to 653.2 g DCB eq. Waste disposal contributes most to this impact, on average 38% across all the scenarios. Manufacture and raw materials are responsible for 20% each and pre-processing for 14%. Although the contribution of both distribution and consumption is small (5% and 3%, respectively), these two stages are the main source of the difference in this impact between the scenarios, with the impact from the other stages being quite similar across the different meal options.

3.1.1.6. Human toxicity potential (HTP). This impact ranges from 254.5 g DCB eq./meal for RM-3 to 382.9 g for RM-8 (Fig. 2g). The consumption stage is the main source of the HTP, contributing around 33%, largely because of the life cycle of electricity used for cooking. For example, the HTP for oven preparation of the chilled meal (RM-1 and RM-5) is 23% higher than for the microwave cooking (RM-2 and RM-6). This difference increases to 32% for the frozen meals. The remaining impact is from manufacturing (17%), disposal (15%) and packaging (12%). Finally, the raw materials contribute 11% with pre-processing and distribution contributing 6% each.

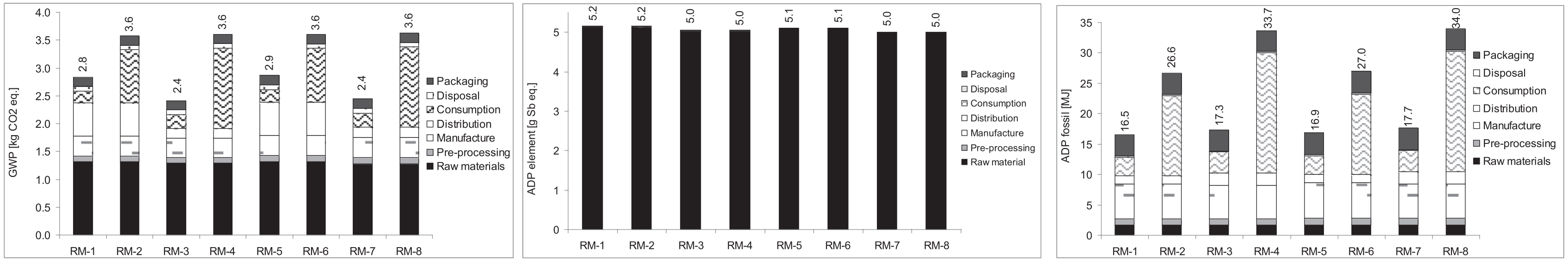
3.1.1.7. Marine aquatic ecotoxicity potential (MAETP). As shown in Fig. 2h, the MAETP increase from 0.6 t DCB eq. for the microwaved meals (RM-1, RM-3, RM-5 and RM-7) to 1.3 t DCB eq./meal for the frozen oven-cooked meals (RM-4 and RM-8). The consumption stage is responsible on average for 31% of this impact, mainly because of the electricity. Therefore, similar to the effect on the HTP, all the scenarios with microwaving have a 41% lower impact for the chilled meals and 52% for the frozen meals, relative to oven cooking. The next largest contributors are meal manufacture with 24% and post-consumer waste disposal with 19%. Pre-processing and distribution are each responsible for 8% while the raw materials and packaging add 5% and 4%, respectively.

3.1.1.8. Ozone layer depletion potential (ODP). The ODP is only sensitive to one parameter – whether the meal is chilled or frozen. It is 11 times higher for the chilled than frozen meal, increasing from 1.5 mg R11 eq./meal to 16.7 mg (Fig. 2i). This is because the distribution stage contributes ~95% to the ODP in the chilled-meal chain. The main reason for this is the manufacturing of R134a – although the refrigerant itself has a zero ODP, other refrigerants used in its manufacture are ozone-depleting substances, particularly R113, R12 and R124 (Ecoinvent, 2010). The other stages contribute less than 2%.

3.1.1.9. Photochemical ozone creation potential (POCP). This impact ranges from 2.4 g C_2H_4 eq./meal for the frozen microwaved meal (RM-3 and RM-7) to 2.7 g for the frozen oven-cooked meal (RM-4 and RM-8; see Fig. 2j). Around 70% of the POCP is due to the ingredients and in particular chicken rearing. The next significant stage and the main differentiating parameter between the scenarios is the consumption stage, contributing 8% for the chilled and 16% for the frozen meal, owing mainly to the electricity used to cook the meal. This is followed by meal manufacturing (~7%), packaging (~4%), pre-processing and distribution (~3% each), all largely related to the energy use.

Table 16
Scenarios for the home-made meals.

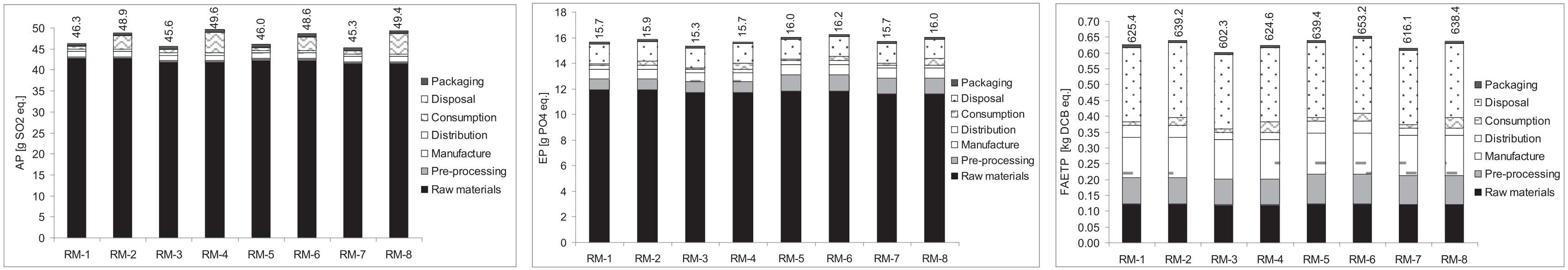
Scenario	Raw materials	Pre-processing	Distribution	Consumption (preparation)
HM-1	Chicken & vegetables: British, conventional Tomato paste: Spanish tomatoes, conventional	Fresh (chilled)	Fresh (chilled)	Chicken roasted in electric oven; vegetables and ready-made tomato sauce cooked on electric hob
HM-2	Chicken, potatoes, tomatoes and carrots: British, organic Onions and peas: British, conventional	As HM-1	As HM-1	As HM-1 with tomato sauce made from fresh tomatoes
HM-3	As HM-1	As HM-1	As HM-1	Vegetables and ready-made tomato sauce cooked in microwave; chicken as HM-1
HM-4	Chicken: Brazilian, conventional All other ingredients: as HM-1	As HM-1	As HM-1	As-HM-1



a) Global warming potential (GWP100)

b) Abiotic depletion potential ($ADP_{elements}$)

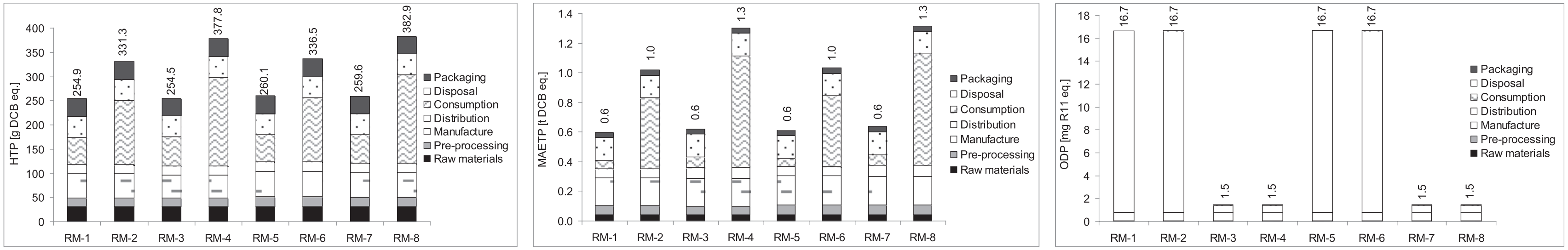
c) Abiotic depletion potential (ADP_{fossil})



d) Acidification potential (AP)

e) Eutrophication potential (EP)

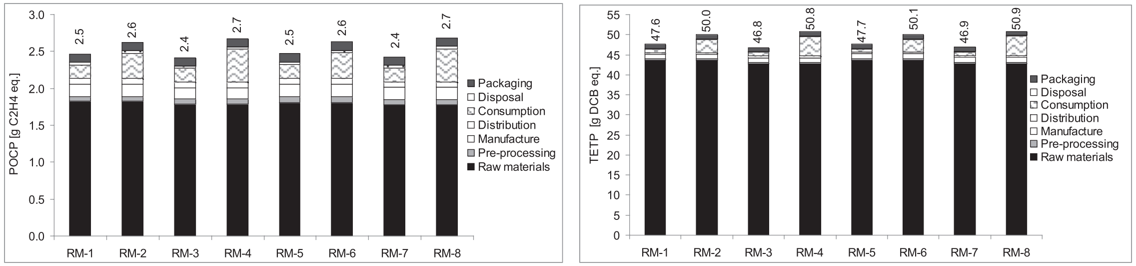
f) Freshwater aquatic toxicity potential (FAETP)



g) Human toxicity potential (HTP)

h) Marine aquatic ecotoxicity potential (MAETP)

i) Ozone layer depletion potential (ODP)



j) Photochemical ozone creation potential (POCP)

k) Terrestrial ecotoxicity potential (TETP)

Fig. 2. Environmental impacts of the ready-made meal for different scenarios showing life cycle contributions. [All impacts expressed per meal. For scenario descriptions, see Table 15].

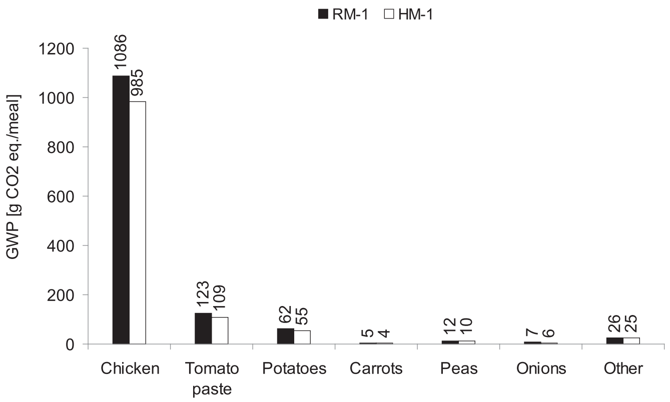


Fig. 3. Contribution of the ingredients to the GWP of the ready (RM-1) and home-made (HM-1) meals.

3.1.1.10. Terrestrial ecotoxicity potential (TETP). As shown in Fig. 2k, the best options for this impact are again the scenarios in which the frozen meal is microwaved, estimated at around 46.9 g DCB eq./meal (RM-3 and RM-7). This is 8% lower than the frozen meal prepared in the conventional oven for which the impact is equal to 50.9 g DCB eq./meal (RM-4 and RM-8). With an average contribution of 89%, the ingredients are the main hotspot for all the scenarios; this is due to the pesticides used in the agricultural stage, particularly in the life cycle of oil. The next contributing stage is consumption with up to 10% for the frozen meal, largely because of the life cycle of electricity used for meal preparation. The contribution of the remaining stages is insignificant.

3.1.2. Influence of ingredient sourcing (scenarios RM-9 to RM-11)

This section considers the effect on the impacts of different ingredient-sourcing options: replacement of the chicken reared in the UK with that imported from Brazil (RM-9), use of British instead of Spanish tomatoes for the tomato sauce (RM-10) and substitution of conventionally-cultivated with organic ingredients (RM-11). All three scenarios are assumed to be the same as RM-1 except for the difference in the source of the ingredients, respectively.

3.1.2.1. Brazilian vs British chicken. As indicated in Fig. 4, replacing British with the Brazilian chicken (RM-1 vs RM-9 scenarios) results in an improvement of four impacts, despite the long-distance transport: the GWP is reduced by 32%, the AP by 75% and the EP and POCP by about 60%. This is due to the lower impacts from chicken rearing for the Brazilian chicken compared to the British. The scenario with the latter option (RM-1) is better marginally for only two impacts: the HTP and TETP, which are lower by 2%. The reason for this is the avoidance of transportation from Brazil and lower impacts from British chicken rearing. The two options are almost identical for the remaining impacts as they are mainly from the consumption, distribution and manufacturing stages which are not influenced by chicken sourcing. Thus on balance, using the Brazilian chicken may be environmentally a better option than using the British chicken, despite the long-distance transport.

3.1.2.2. Spanish vs British tomatoes. As can be seen in Fig. 4, the Spanish tomato paste (RM-10) is better for five impacts with the remaining impacts being quite similar between the two options. The greatest difference in favour of Spanish paste is found for the $ADP_{elements}$ (86%), EP (39%), GWP (24%), AP (11%) and POCP (6%). There are two main reason for this: different use of fertilisers to grow the tomatoes in the two countries and the use of electricity for heating greenhouses, where the majority of tomatoes are grown in the UK. Therefore, based on these results, scenario RM-1 using the Spanish tomato paste is arguably a better option, regardless of the transport from Spain. These findings, together with the those for the Brazilian chicken discussed in the previous section, provide a further illustration that ‘food miles’ typically do not contribute much to the impacts of food and that other life cycle stages are often much more significant.

3.1.2.3. Conventional vs organic ingredients. Comparing conventional (RM-1) and organic ingredients (RM-11) in Fig. 4 indicates that using the latter leads to an increase in five impacts, with the remaining six impacts being similar between the two meal options. In particular, the greatest increase is found for the $ADP_{elements}$ (69%), followed by the EP (35%), AP (19%) and POCP (15%). The GWP also goes up by ~5%. The lower yield in the organic production systems is the main reason for the higher impacts for RM-11. Therefore, the meal with the conventional ingredients appears to be environmentally a better option.

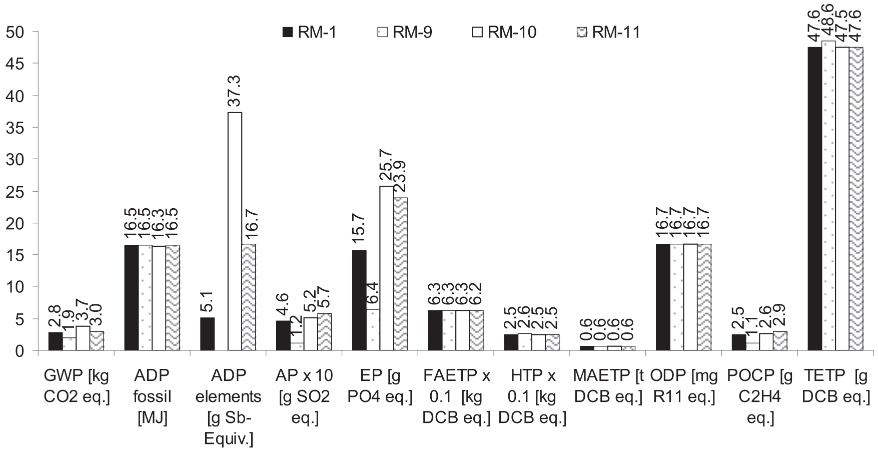


Fig. 4. The influence of ingredient sourcing on the environmental impacts of the ready-made meal. [All impacts expressed per meal. $ADP_{elements}$: Abiotic depletion potential for elements; ADP fossil: Abiotic depletion potential for fossil fuels; AP: Acidification potential; EP: Eutrophication potential; FAETP: Freshwater aquatic ecotoxicity potential; GWP: Global warming potential (100 years); HTTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone depletion potential; POCP: Photochemical oxidant creation potential; TETP: Terrestrial ecotoxicity potential. $ADP_{elements}$ for the Brazilian chicken is not shown owing to a lack of data. Some impacts have been scaled to fit. The original values can be obtained by multiplying with the factor shown in brackets against the relevant impacts.].

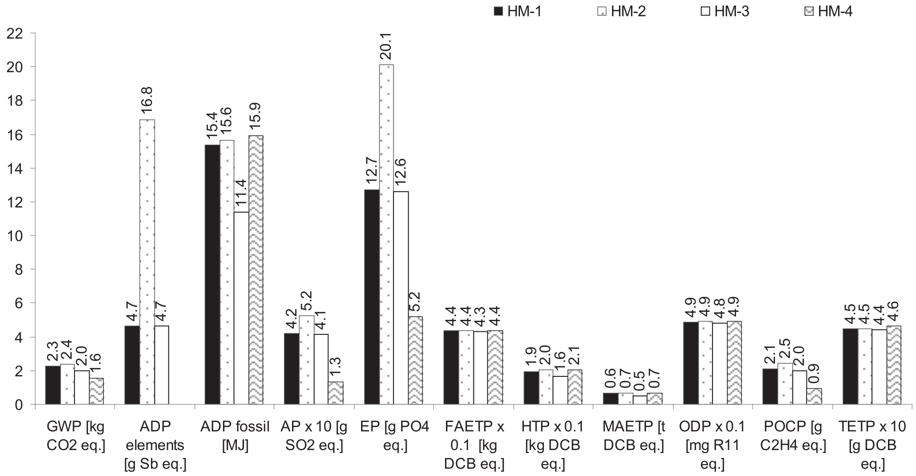


Fig. 5. Environmental impacts of the home-made meal for different scenarios. [All impacts expressed per meal. For impacts nomenclature, see Fig. 4. $ADP_{elements}$ for the Brazilian chicken is not shown owing to a lack of data. Some impacts have been scaled to fit. The original values can be obtained by multiplying with the factor shown in brackets against the relevant impacts.].

3.2. Home-made meal

Fig. 5 shows the environmental impacts of the home-made meal HM-1 with the contribution of different life cycle stages given in Fig. 6. As indicated in Fig. 6, unlike the equivalent ready-made meal RM-1, the contribution to the impacts is quite different for HM-1: as there is no manufacturing and little pre-processing of the ingredients before they reach the retailer and then the consumer, the majority of the impacts are from the ingredients and the consumption stage. The exception to this are FAETP which is largely due to post-consumer waste disposal and ODP which is from the distribution stage.

As shown in Fig. 5, using organic ingredients (HM-2) instead of conventional (HM-1) has a similar effect on the impacts as seen for the organic ready-made meal RM-11 (see the previous section). Specifically, the GWP increases from 2.3 kg CO_2 eq. to 2.4 kg CO_2 eq. The other affected impacts are the $ADP_{elements}$ which goes up by 72%, AP by 20%, EP by 40%, HTP by 4% and POCP by 16%. Again, the main reason for the higher impacts is the lower yield of the organic produce compared to the conventionally-cultivated ingredients. The change in the remaining impacts is small (<2%).

Fig. 5 also reveals that cooking the vegetables on the hob (HM-1) has higher impacts than cooking in the microwave (HM-3). The greatest improvements are found for the GWP (13%), ADP fossil (26%), HTP (16%) and MAETP (26%). The other impacts improve on average by 2%. These changes in the results are congruent with the contribution to these impacts of meal preparation in the consumption stage (see Fig. 6).

The meal with the Brazilian chicken (HM-4) also leads to improvements in the impacts: the GWP is lower by 31%, AP by 68%, EP by 59% and POCP by 55%. The TETP and HTP are higher, however, by 3% and 6%, respectively. The remaining impacts are largely unaffected. A similar pattern was found for the ready-made meal, as discussed in the previous section.

Therefore, it can be concluded from these results that preparing the home-made meal using the Brazilian chicken and cooking the conventionally-grown vegetables in the microwave is the best option environmentally – these represent a combination of best options from scenarios HM-3 and HM-4.

3.3. Comparison of ready and home-made meals

The environmental impacts of the ready and home-made meals are compared in Fig. 7 for the best options for the ready-made meal (RM-3 and RM-9) and for the home-made meal prepared in a conventional way (HM-1 and HM-4) rather than using microwave as this is a more prevalent practice in the UK for home cooking. For reference, the results for the home-made meal with organic ingredients (HM-2) are also shown. The results indicate that the impacts of preparing the meal at home using conventionally-cultivated

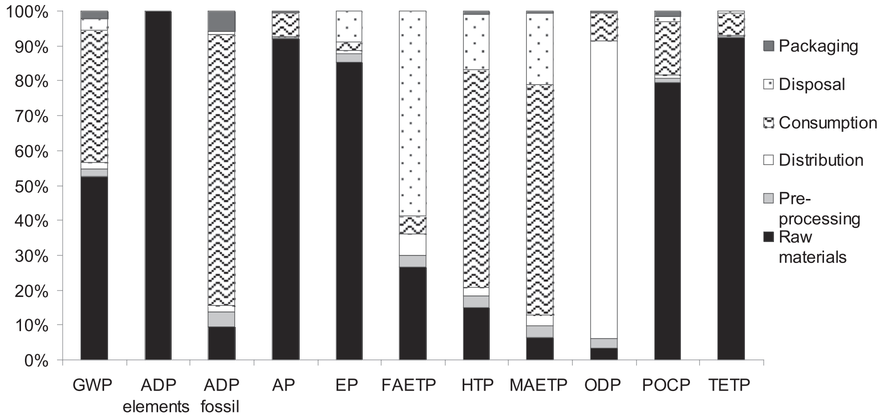


Fig. 6. Contribution of the life cycle stages to the impacts of the home-made meal (scenario HM-1). [For impacts nomenclature, see Fig. 4.].

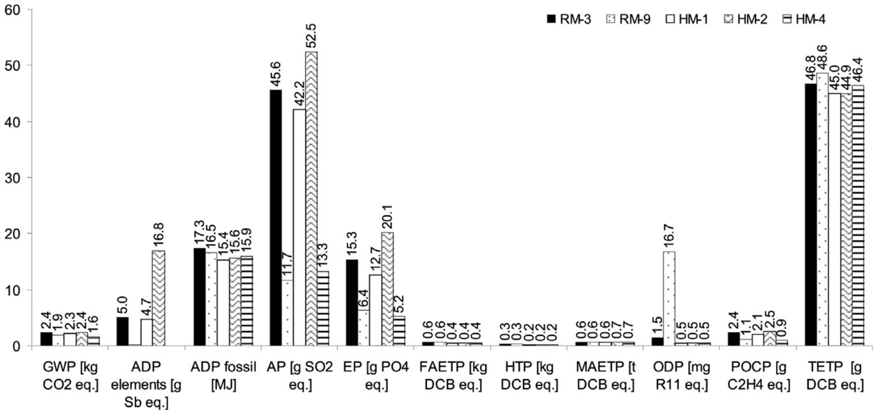


Fig. 7. Comparison of environmental impacts of the ready and home-made meals. [All impacts expressed per meal. Note that $\mathrm{ADP_{elements}}$ for the Brazilian chicken is not shown owing to a lack of data. For impacts nomenclature, see Fig. 4.].

ingredients (HM-1) are lower than for the equivalent ready-made meal (RM-3) for ten out of the 11 impacts considered. The greatest improvement is found for the ODP which is 3 times lower with the remaining eight impacts reduced from 6% (GWP) to 28% (FAETP). The main reason for the reduction in the impacts is the avoidance of manufacturing and the related waste as well as fewer storage stages in the life cycle of the home-made meal. However, the MAETP is higher by 7% because of the higher electricity consumption for the preparation of the home meal compared to the ready-made.

A similar trend is found when the home-made meal with the Brazilian chicken (HM-4) is compared with the ready-made meal (RM-3), but the improvements for some of the impacts are much greater. For example, the GWP is 35% lower for the home-made meal; the AP, EP, ODP and POCP are all lower by around 3 times. Again, the only impact that is worse for the home-made meal is MAETP which is 8% higher.

However, a different trend is observed when the home-made meal with the British ingredients (HM-1) is compared to the ready-made meal prepared with the Brazilian chicken (RM-9). In this case, the ready-made meal is a better option for five impacts: the GWP, AP, EP, MAETP and POCP. The difference in the impacts ranges from 9% for the MAETP to 3.6 times for the AP. This is largely due to the differences in the agricultural impacts related to the British and Brazilian chickens. However, the meal prepared at home is a better option for the $\mathrm{ADP_{fossil}}$ (7% lower), FAETP (30%), HTP (26%), ODP (34 times lower) and TETP (7%), for the same reasons explained for the comparison with RM-3. Moreover, when both types of meal are prepared with the Brazilian chicken (RM-9 and HM-4), the home-made option has eight impacts lower than the ready-made meal; the largest reduction is found for the ODP, with a 34 times lower value. The other impacts are lower by between 4% for the $\mathrm{ADP_{fossil}}$ and TETP to 30% for FAETP. However, two impacts are higher for the home-made meal: AP by 12% and MAETP by 10%.

If, on the other hand, the organic home-made meal (HM-2) is compared to the ready-made meal (RM-3) the picture is mixed, with each being better for half the impacts considered. For example, the home-made meal has lower FAETP and HTP lower by 28% and 21%, respectively, but the ready-made meal has a 3 times lower $\mathrm{ADP_{elements}}$. A similar trend is found when comparing the ready-made meal with the Brazilian chicken (RM-9) and the organic home-made meal (HM-2). The ready-made meal has 18% lower GWP and ~70% lower AP and EP. However, the ODP is still 34 time higher.

Therefore, these results suggest that the home-made meal using ingredients from conventional farms is a better option than the ready-made meal for most environmental impacts. Thus, it could be concluded that home-made meals are more sustainable environmentally than the ready-made, for the assumptions used in this study. Among the home-made meal options, the one with the Brazilian chicken (HM-4) has the lowest GWP (1.6 kg CO_2 eq./meal; see Fig. 7), one of the main policy drivers in the UK and Europe. This meal cooked in a microwave instead in the electric oven and the hob would be a better option still. However, that would require significant changes in consumer lifestyle, cooking habits and abilities as well as taste, the consideration of which is outside the scope of this paper.

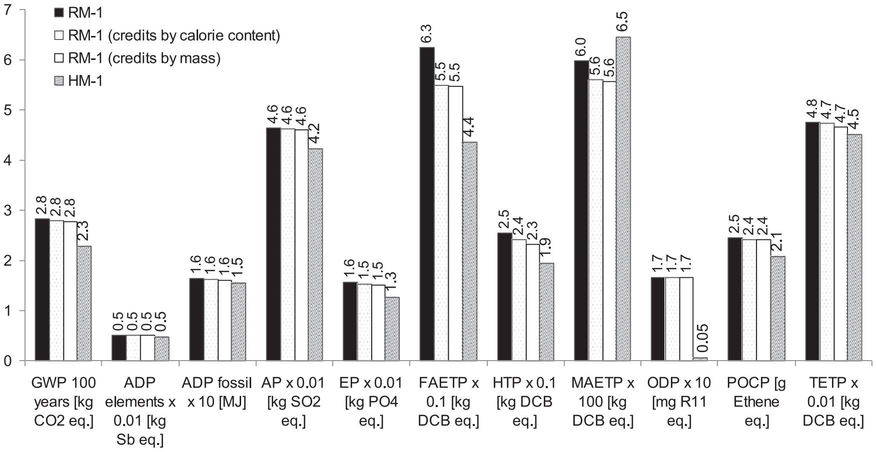
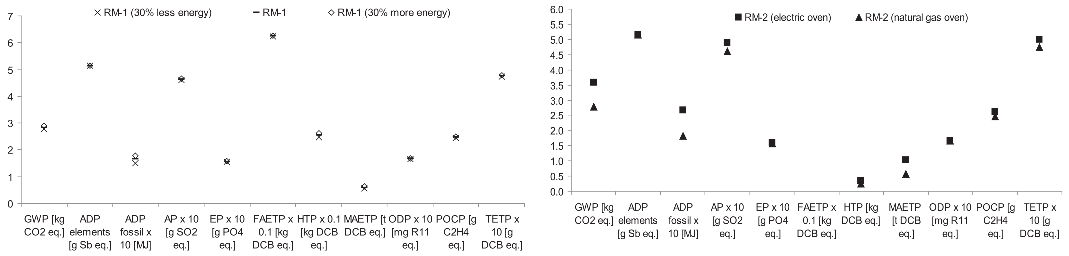
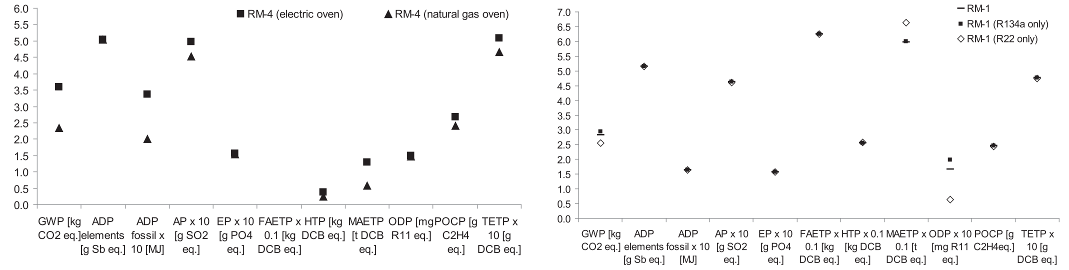


Fig. 8. Sensitivity analysis for the ready-made meal: the influence of credits for waste from pre-processing used as animal feed. [All impacts expressed per meal. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit. The original values can be obtained by multiplying with the factor shown in brackets against the relevant impacts.].



a) Influence of energy efficiency in the manufacture of chilled ready-made meal

b) Influence of using gas or electricity oven to cook of chilled ready- made meal at home



c) Influence of using gas or electricity oven to cook frozen ready-made meal at home

d) Influence of the type of refrigerant

Fig. 9. Sensitivity analysis for the ready-made meal. [All impacts expressed per meal. For impacts nomenclature, see Fig. 4. For assumptions on energy use by appliances, see Table 7. Some impacts have been scaled to fit. The original values can be obtained by multiplying with the factor shown in brackets against the relevant impacts.].

3.4. *Sensitivity analysis*

This section examines the effect on the results of some other parameters not considered in the scenarios that could potentially influence the results. This is carried out first for the ready-made meal and then for the meal prepared at home. The results are presented in Fig. 9 and Fig. 10, respectively, and are discussed below.

3.4.1. *Ready-made meal*

Sensitivity of the results for the ready-made meal is examined for the following parameters:

i) credits for vegetable waste from pre-processing for use as animal feed;
ii) energy efficiency in the manufacturing process;
iii) source of energy for the oven used by the consumer to cook the meal at home; and
iv) type of refrigerant used.

3.4.1.1. Credits for waste as animal feed. As mentioned in Section 2.2.2, the vegetable waste from the pre-processing stage has been assumed to be landfilled. This section examines the influence of this assumption on the results by assuming that the waste is used as animal feed, replacing wheat as the most widely used feed in the UK (Defra, 2013).

The system has been credited for animal feed using two bases: mass and calorie content of the waste to displace the equivalent amount of wheat. The amount of vegetable waste generated in the pre-processing stage is equal to 33.82 g[1] so that the system has been credited for this amount of animal feed when using the mass basis. For the credits based on the calorie content, using the mass contribution of different vegetables (see Table 2) and their respective calorie content,[2] the total calorie content of vegetable waste is estimated at 19.32 cal/kg. Taking into account the calorie value for the wheat,[2] this amount of waste replaces 5.4 g of wheat per meal so that the system is credited for this amount of animal feed.

Scenario RM-1 is considered as an example and the results are compared to HM-1. As indicated in Fig. 8, the effect on the results is small, with the impacts reducing on average by around 4% when the credits are made on the mass basis and 3% on the basis of calorie content. The greatest improvement is for the toxicity-related impacts and particularly the FAETP which is 12% lower. This is due to the avoidance of these impacts from wheat cultivation. However, even with these credits, the equivalent home-made meal (HM-1) still remains a better option across all the impacts except for the MAETP, as discussed before.

3.4.1.2. Energy efficiency. Energy use in the manufacturing process can differ from producer to producer depending on the type and age of equipment. For this reason, different energy use values have been considered within the sensitivity analysis, ranging from 30% higher to 30% lower compared to the original value assumed in the study (for the latter, see Table 5). The results given in Fig. 9a indicate that the environmental impacts improve only slightly with the energy efficiency, on average by 2% across all the impacts. The highest effect is observed for the ADP_{fossil} which reduces by 8% for a 30% reduction in energy use. This is followed by the MAETP and HTP which go down by 6% and 3%, respectively; the GWP is reduced by around 2%. The effect on the other impacts is small (<1%). Therefore, these findings suggest that the results of the study are robust with respect to the originally assumed energy use in the manufacturing process.

3.4.1.3. Electric vs gas ovens. In the UK, both electric and natural gas ovens are used widely. The study has assumed the use of electric ovens (see Table 7) so that the influence on the impacts of using gas ovens is considered here. These results are compared in Fig. 9b and c for the chilled (RM-2) and frozen meal (RM-4), respectively. As

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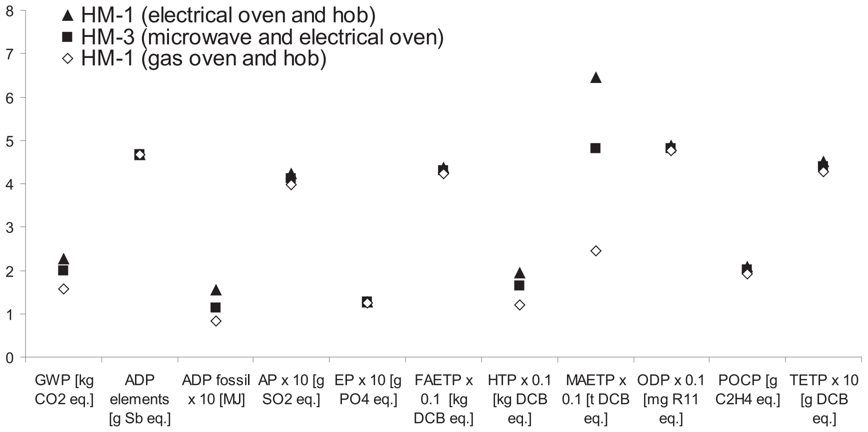
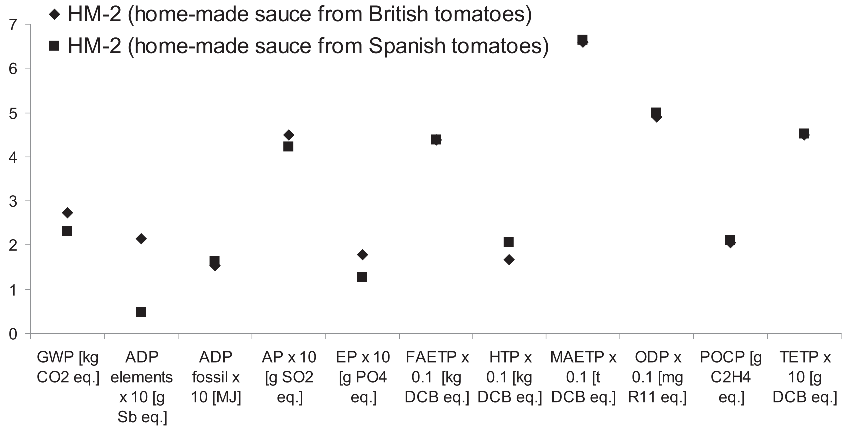
[1] Based on the total amount waste in the life cycle of the meal given in Table 4 (excluding post-consumer waste), the total amount of vegetables needed per meal in the pre-processing stage is 259.32 g. Assuming 15% waste in that stage gives 33.82 g.

[2] Calorie content in kcal/100 g: potatoes: 58; onions: 44; carrots: 42; peas: 80.7; wheat: 358.



a) Influence of using gas or electricity appliances to cook the home-made meal



b) Influence of using Spanish instead of British tomatoes to cook home-made tomato sauce

Fig. 10. Sensitivity analysis for the home-made meal. [HM-2 has been modified from the original by substituting organic with conventionally-grown ingredients. For assumptions on energy use by appliances, see Table 8. All impacts expressed per meal. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit. The original values can be obtained by multiplying with the factor shown in brackets against the relevant impacts.].

shown, the impacts are lower if natural gas is used instead of electricity. This effect is more pronounced for the frozen than the chilled meal, with the impacts reducing on average by 12% for the former and 18% for the latter. The greatest reduction is observed for the MAETP (44% and 55% for the chilled and frozen meal, respectively) and GWP (22% and 35%, respectively). The only two exceptions to this trend are the $ADP_{elements}$ and ODP which remain the same as these impacts are not affected much by the consumption stage (see Fig. 2b&i).

3.4.1.4. Type of refrigerant. Refrigeration is an important contributor to some of the impacts from the ready-made meal, particularly the GWP and ODP. In this study, the refrigerants used are ammonia (in RDC), R22 (manufacturing) and R134a (retail and transportation). In order to analyse their effect on the impacts, three options are considered within the sensitivity analysis: only R134a or R22 are used; only R134a is used; and only R22 is used in the whole supply chain. As can be seen in Fig. 9d, using only R134a increases the GWP by 4% and ODP by 16% compared to the base case (RM-1). The other impacts remain unchanged. When R22 is used instead, the impacts are reduced relative to the base case: the GWP by 10% and ODP by 62%. However, the MAETP goes up by 10% owing to the higher impact in the manufacture of this refrigerant. Similar to the option with R143a, the other impacts are unaffected.

3.4.2. *Home-made meal*

This section considers the effect on the environmental impacts of the source of energy used for cooking the meal and the provenance of tomatoes for the sauce. The following options are examined:

i) preparing the meal using gas appliances (oven and hob); and
ii) preparing the home-made tomato sauce using either Spanish or British tomatoes.

3.4.2.1. Gas vs electrical appliances. Fig. 10a compares the impacts of using gas appliances to the base case which assumed the use of an electric oven and a hob (HM-1) or a combination of an electric oven and a microwave (HM-3) to cook the meal. As can be seen, the use of natural gas reduces all impacts on average by 18% compared to HM-1 and by 12% compared to HM-3. The latter may at first look surprising as it would be expected that the microwave option has lower impacts than gas but HM-3 also uses an electric oven (for roasting the chicken) which has higher impacts than the gas. The biggest improvements in both cases are found for the GWP (31% and 21% compared to HM-1 and HM-3, respectively), ADP_{fossil} (46% and 27%), HTP (38% and 26%) and MAETP (62% and 49%). Therefore, using gas appliances would make home-made meal even more environmentally sustainable than the ready-made meal with the impacts being on average lower by 33% relative to the best option (RM-3).

3.4.2.2. Home-made tomato sauce from British vs Spanish tomatoes. For the purposes of this sensitivity analysis, HM-2 scenario is considered as it involves home-made tomato sauce. However, it has been modified by replacing the organic with the ingredients sourced from conventional farming systems for comparability with HM-1, which assumes conventional ingredients and ready-made tomato sauce.

Substituting British tomatoes with the Spanish to make a home-made tomato sauce reduces four environmental impacts: the GWP by 15%, $ADP_{elements}$ by 78%, AP by 6% and EP by 29% (Fig. 10b). This is due to the avoidance of electricity-heated greenhouses used to grow British tomatoes. The remaining impacts are largely unaffected, except for the HTP which increases by 18% owing to the difference in fertilisers used in the two countries. Comparison of the impacts between the ready-made tomato sauce (HM-1 in Fig. 5) and that prepared at home (HM-2 with Spanish tomatoes in Fig. 10b) reveals that there is little difference between the two options (<2%). Finally, the impacts from HM-2 with the Spanish tomatoes are on average 17% lower than for the best ready-made meal option (RM-3), except for MAETP which is 10% higher. A similar trend was found when comparing HM-1 with RM-3 (see Fig. 7).

4. Conclusions

This paper has compared the life cycle environmental impacts of a ready and home-made meal consisting of roast chicken meat, vegetables and tomato sauce. The results suggest that the impacts of preparing the meal at home from scratch are lower than for the equivalent ready-made meal. The main reasons for this are the avoidance of manufacturing, reduction in refrigerated storage and a lower amount of waste in the life cycle of the home-made meal.

For the ready-made meal options considered in the study, the lowest impacts are found for the frozen meal prepared from fresh ingredients and heated at home in a microwave. This is due to the higher usage and leakage of refrigerants during storage of the chilled meal at retailer because they are kept in open refrigerators while frozen meals are stored in closed cabinets. The worst option for most impacts is the frozen meal with frozen ingredients that is heated in an electric oven. For some of the impacts, consumer choice of the heating method is the most important differentiating factor between the different ready-made meal options considered. For example, cooking the frozen meal in an electric oven has a 6.5 times higher GWP than microwaving the chilled meal. Another differentiator is whether the meal is chilled or frozen with the former having a 15% higher global warming potential than the latter for the same heating method. The type of refrigerant used in the supply chain also influences the results, with R22 being the best option for the global warming potential and ozone layer depletion but worst for marine ecotoxicity. The contribution of packaging is also important for some impacts, including GWP, depletion of fossil fuels and human toxicity.

In addition to the consumer choice of the cooking method, another hotspot for both types of meal are the ingredients. Using organic instead of conventional ingredients leads to higher impacts. Sourcing chicken and tomatoes from Brazil and Spain, respectively, reduces environmental impacts of the meals compared to sourcing them from the UK, despite the long-distance transport. This finding is in contrast to the concept of ‘food miles’ widely publicised in an attempt to encourage consumers to buy locally to help reduce the environmental impact of food. However, as the results of this work suggest, transport is not a significant contributor to the impacts and that, instead, the other life cycle stages mentioned above should be targeted for improvements.

Thus, this work demonstrates that producers, retailers and consumers could all play a role in reducing the environmental impacts of food by making more informed choices. In particular, producers should consider sourcing their ingredients taking into account a growing knowledge and information available on life cycle environmental impacts of different ingredients. Furthermore, both producers and retailers should work on reducing the amount of packaging and waste in the supply chain. Minimising refrigeration time and using low-impact refrigerants would also lead to environmental improvements. Retailers should also replace open with closed refrigerators – the concern that this may inconvenience and deter the consumer may be unfounded as closed display cabinets are becoming common practice in some countries. However, this ‘choice-editing’ may require a concerted action by retailers to ensure that the replacement is carried out across the sector to avoid potentially disadvantaging retailers who make the change compared to those who opt out.

Furthermore, consumers should consider preparing meals at home more often rather than buying ready-made food and cooking using gas instead of electrical appliances, or better still, using a microwave. One of the most significant behavioural changes needed, though, is reducing post-consumer waste – given that one third of food is thrown away globally, this is the single most important factor for reducing the environmental impacts of food. In the specific case considered here, a quarter of the meal is estimated to be wasted by the consumer which means that the impacts related to the ingredients would be reduced by a quarter just by avoiding this waste as the amount of raw materials required to make the meal would be that much lower. Unlike some other options, reducing consumer food waste should be relatively simple to achieve as it does not require lifestyle changes and has direct financial benefits for the consumer. However, most consumers do not make a connection between food waste and environmental impacts so that an intensive awareness-raising programme could help reduce the amount of post-consumer waste.

However, the above choices by the different actors will often be driven by other issues such as cost, availability, health, cooking abilities, taste, convenience and lifestyle. These are particularly important for consumers and, for most, the choice is unlikely to be either a home or a ready-made meal; conventional or organic ingredients; microwave or oven etc., but rather some combination of different options, depending on their individual circumstances. Nevertheless, it is important to understand the life cycle impacts of producer, retailer and consumer choices related to meals – currently, there is scant information available requiring much more research in this area.

Acknowledgements

The authors are grateful to RCUK (grant no. EP/K011820) and BECAS Chile for sponsoring this research.

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