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Life cycle environmental impacts of ready-made meals considering different cuisines and recipes

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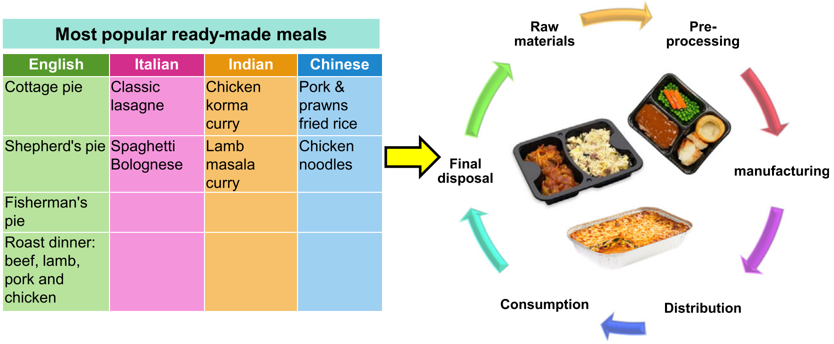
HIGHLIGHTS

- Roast dinners, especially pork, have the lowest environmental impacts.
- Spaghetti Bolognese, cottage pie and lamb curry exhibit the highest impacts.
- A third of meat substituted by meat replacements reduces impacts by up to up to 27%.
- Annual ready-made meal consumption in the UK generates 13 Mt. CO_2 eq.
- This represents up to 15% of personal carbon budgets related to food intake.

GRAPHICAL ABSTRACT



Most popular ready-made meals

English	Italian	Indian	Chinese
Cottage pie	Classic lasagne	Chicken korma curry	Pork & prawns fried rice
Shepherd's pie	Spaghetti Bolognese	Lamb masala curry	Chicken noodles
Fisherman's pie			
Roast dinner: beef, lamb, pork and chicken			

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ABSTRACT

Convenience is one of the main determinants of modern society where products, such as ready-made meals, play a key role. However, the continuing growth of this market has raised environmental concerns, which have not been well studied yet. This paper evaluates life cycle environmental impacts of meals consumed in the UK, the second largest consumer of ready-made meals in the world, after the US. Thirteen representative ready-made meals are evaluated in the British, Italian, Chinese and Indian cuisines, considering variations in recipes found on the market, as well as different meat replacement options. The results suggest that environmentally the most sustainable meal option is pork roast dinner while the worst alternatives are spaghetti Bolognese, cottage pie, lamb masala curry and lasagne. For example, the global warming potential of pork roast is 2.1 kg CO_2 eq. and that of lasagne 5 kg CO_2 eq. The ingredients contribute >50% to the impacts, followed by the distribution (~14%) and manufacturing (~12%) stages. Using seitan or soy granules as meat replacements improves five out of 11 impacts considered, including global warming potential, by up to 27%; the other impacts are largely unaffected. However, if tofu is used, four impacts are improved while four others are worsened. The annual consumption of ready-made meals in the UK accounts for GHG emissions of 12.89 Mt. CO_2 eq., equivalent to emissions of a whole country, such as Jamaica. This contributes 15% to the emissions from the UK food and drink sector. It also represents 8% and 15% of the personal carbon budgets for food related to climate targets of 2 °C and 1.5 °C, respectively. The results of the study will be of interest to both food manufacturers and consumers, showing how their choices affect the environmental sustainability of this fast-growing sector.

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1. Introduction

Time saving and convenience are significant drivers of consumption patterns. As a result, the ready-made meal industry has thrived globally. A clear example of this is the fast growth of these, typically Western products, in markets such as Asia, Latin America and Eastern Europe (Key Note, 2013; Statista, 2017). The world's largest consumers, however, are still based in the West: the US and the UK (Key Note, 2013), with an estimated per-capita consumption of 27.8 kg and 19 kg, respectively (Statista, 2018). In the UK, the sector has exhibited fast growth since 2008, where its retail-price value rose from £1.62 bn to £2.09 bn in 2014 (Key Note, 2013, 2015). The market is dominated by chilled ready-made meals with 70% of the share, with the rest occupied by the frozen meals segment. Since 2009 the chilled-meals market has grown by 19.7%, valued at £1.38 bn in 2013, estimated to reach £1.8 bn by 2019 (Key Note, 2014; Key Note, 2015).

Although this fast growth has contributed to the overall UK economy, the environmental pressures of the agri-food supply chain have been affecting climate change and resource use, among other areas of concern. For instance, in 2011, the UK greenhouse (GHG) emissions from the agri-food sector were estimated at 176 Mt. CO_2 eq., the majority of which (~31%) was due to farming and fishing, with the rest being from food manufacturing and retail (7% each) and households (10%) (Defra, 2014). Food waste is also an important environmental issue, with the UK food and drink sector generating 10 Mt. annually. Around 7.3 Mt. of that is produced by consumers, nearly six times more than by food manufacturers (1.3 Mt) (Defra, 2017).

Despite their growing importance worldwide, there is scant information on the environmental impacts of ready-made meals, with only three life cycle assessment (LCA) studies conducted to date. Two of these are in based in Scandinavia, specifically in Sweden (Berlin and Sund, 2010) and Finland (Saarinen et al., 2012), and the third in the UK (Schmidt Rivera et al., 2014). The study in Sweden considered two meals (pork and chicken-based), estimating primary energy demand, global warming potential, acidification and eutrophication. In addition, a screening assessment of six other meals was carried out but only for global warming potential. The Finnish study focused on school lunches to compare six types of home and ready-made meals, focusing on two impacts: global warming potential and eutrophication. Finally, the study based in the UK estimated a number of environmental impacts of a ready-made chicken dinner (Schmidt Rivera et al., 2014).

Therefore, there is a lack of comprehensive LCA studies analysing a greater variety of ready-made meals and impacts, as well as the parameters that influence them, such as different cuisines and recipes. Hence, this work seeks to determine the environmental sustainability of a range of ready-made meals, focusing on consumption in the UK as the world's second highest consumer of these products. Furthermore, variations in recipes across the market are also considered in order to examine their effect on the impacts. The study also explores opportunities to improve the environmental sustainability by incorporating meat replacements into the recipes. The methodological approach applied in the research is described in the next section; the results are discussed in Section 3 and followed by conclusions and recommendations in Section 4.

Table 1
Cuisines and corresponding ready-made meals with side dishes selected for the study.

Cuisine	Ready-made meal	Side dishes
British	Cottage pie	–
	Shepherd's pie	–
	Fisherman's pie	–
	Beef roast dinner	Yorkshire pudding and vegetables[a]
	Lamb roast dinner	~II~
	Pork roast dinner	~II~
	Chicken roast dinner	~II~
Italian	Classic lasagne	–
	Spaghetti Bolognese	–
Indian	Chicken korma curry	Rice
	Lamb masala curry	Rice
Chinese	Pork and prawns fried rice	–
	Chicken noodles	–

[a] Potatoes, carrots and peas.

2. Methods

LCA has been used to evaluate the environmental sustainability of ready-made meals. The study has been carried out following the ISO 14040/14044 methodology (ISO, 2006a, 2006b), as detailed in the next sections.

2.1. Goal and scope

The aim of this study is to estimate and compare the environmental sustainability of representative ready-made meals manufactured and consumed in the UK. The focus is on chilled meals due to their large market share (70%). A further goal is to identify improvement opportunities through recipe formulations and make recommendations to the industry and consumers.

To be considered representative and selected for the study, the chilled ready-made meals had to satisfy the following criteria:

- belong to one of the most popular cuisines;
- be produced by different manufacturers; and
- be available at all major retailers.

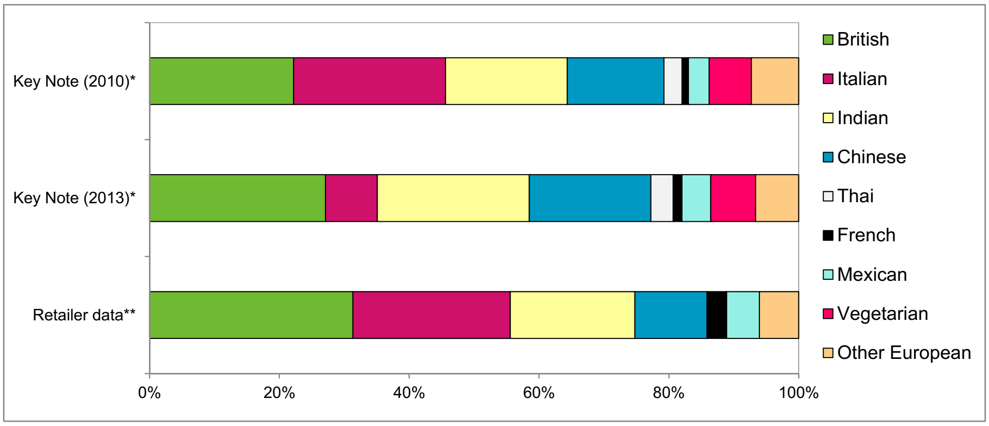


Fig. 1. The UK chilled ready-made meals market share by consumer preference and annual sales. [* Data based on consumer preferences survey. ** Data based on annual sales in 2010.]

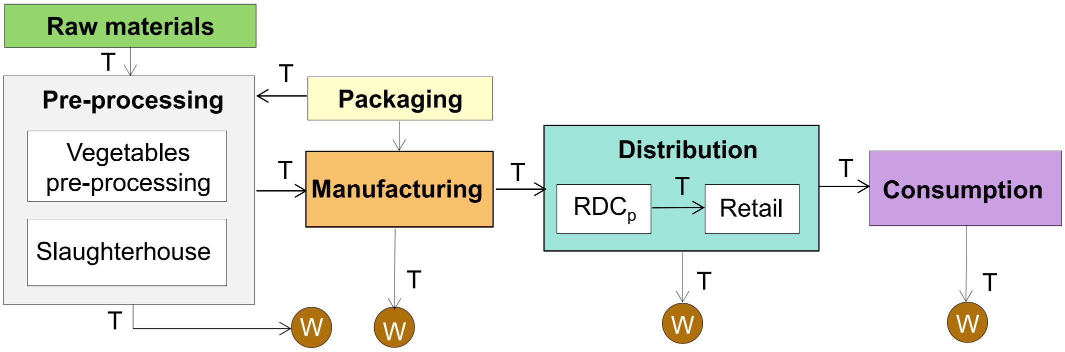


Fig. 2. System boundaries considered in the study. (RDCp: regional distribution centre of final products. T: transport; W: waste management.)

Table 2
Composition of the ready-made meals considered in this study based on the market analysis[a].

Ingredients [g/meal]	Cottage pie	Shepherd's pie	Fisherman's pie	Beef roast	Lamb roast	Pork roast	Chicken roast	Classic lasagne	Spaghetti Bolognese	Chicken korma curry	Lamb masala curry	Pork & prawns fried rice	Chicken noodles
Rice	–	–	–	–	–	–	–	–	–	134	134	196.8	–
Pasta/noodles	–	–	–	–	–	–	–	47	119	–	–	–	111.6
Mashed potatoes	180	180	164	–	–	–	–	–	–	–	–	–	–
Potatoes	167	167	153	–	–	–	–	–	–	–	–	–	–
Milk	7	7	7	–	–	–	–	–	–	–	–	–	–
Butter	5	5	5	–	–	–	–	–	–	–	–	–	–
Meat													
Beef	58	–	–	41	–	–	–	72	58	–	–	–	–
Lamb	–	58	–	–	41	–	–	–	–	–	74	–	–
Pork	–	–	–	–	–	41	–	–	–	–	–	57.6	–
Chicken	–	–	–	–	–	–	75.6	–	–	74	–	–	65.9
Fish	–	–	59	–	–	–	–	–	–	–	–	–	–
Prawns	–	–	18	–	–	–	–	–	–	–	–	9	–
Veg. & others													
Potatoes	–	–	–	93.6	93.6	93.6	93.6	–	–	–	–	–	–
Carrots	–	6	–	44.3	44.3	44.3	44.3	14	19	–	–	–	45
Peas	–	11	17	43.2	43.2	43.2	43.2	–	–	–	–	25.6	–
Onions	59	15	–	–	–	–	13.2	23	49	113	35	18.9	45
Tomatoes	–	15	–	–	–	–	–	94	76	–	87	–	–
Tomato paste	3	–	–	–	–	–	–	–	–	–	3	–	–
Cream	–	–	–	–	–	–	–		–	20	9	–	–
Flour	1	–	4	10.9	10.9	10.9	4	9	–	2	–	–	–
Sugar	–	–	–	–	–	–	–		–	7	–	–	–
Wine	15	–	–	–	–	–	–		27	–	–	–	–
Beef stock	39	73	–	106	106	106	75.6		–	–	–	–	–
Milk			87	12.9	12.9	12.9	–	88	–			–	–
Butter			9	–	–	–	–	9	–			–	–
Bread	–	–	–	–	–	–	5.2	–	–	–	–	–	–
Eggs	–	–	–	7.1	7.1	7.1	3.4	–	–	–	–	20.4	–
Soy sauce	–	–	–	–	–	–	–	–	–	–	–	12.8	92.5
Oil (veg./olive)	5	2	–	–	–	–	0.9	3	11	8	17	18.9	–
Salt	1	1	1	1	1	1	1	1	1	2	1	–	–
Total	360	360	360	360	360	360	360	360	360	360	360	360	360

[a] The recipes are based on information from manufacturers (product labels) and home-made recipes (BBC food, 2014).

Table 3
Variations in the recipes of the ready-made meals based on the market analysis.[a]

	Cottage pie		Shepherd's pie		Fisherman's pie		Beef/lamb/pork roast		Chicken roast		Classic lasagne		Spaghetti Bolognese		Lamb masala curry		Chicken korma curry		Pork & prawns fried rice		Chicken noodles	
Ingredient [%] group	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Rice/mashed potatoes/pasta	60	47	50	50	48	41	50.3	57	50.3	57	13	13	37	23	41	36	41	36	85	81	37	25
Meat & sauce/gravy	40	53	50	50	52	59	–	–	–	–	87	87	63	77	59	64	59	64	–	–	–	–
Meat	44	14	40	*23*	29	14	13	9	22	20	27	16	31	17	50	26	50	26	15	19	20	17
Sauce/gravy	56	86	60	*77*	23	45	36.7	34	27.7	23	73	84	69	83	50	74	50	74	–	–	55	46

[a] The recipe variations are based on the assessment of available products in the main UK supermarkets: Asda (2014), Sainsbury's (2014), Tesco (2014), Morrisons (2014), Iceland (2014) and Lidl (2014).

Table 4
Summary of ingredients, country of origin and LCA data sources.

Ingredients	Country of origin	LCA data[a]	Source
Beef	UK	UK	Williams et al. (2006)
Lamb	UK	UK	Williams et al. (2006)
Pork	UK	UK	Williams et al. (2006)
Chicken	UK	UK	Williams et al. (2006)
Eggs	UK	UK	Williams et al. (2006)
Fish (mackerel[b])	Spain	Spain	Vázquez-Rowe et al. (2010)
Prawns (shrimp[c])	Denmark	Denmark	Nielsen et al. (2003)
Potatoes	UK	UK	Williams et al. (2006)
Tomatoes	Spain	Spain	Antón et al. (2005)
Tomato paste[d]	UK	Spain	EC (2010), FAO (2009)
Carrots	UK	Denmark	Nielsen et al. (2003)
Onions	UK	Denmark	Nielsen et al. (2003)
Peas	UK	Denmark	Milà i Canals et al. (2008)
Wheat	Switzerland	Switzerland	Ecoinvent (2009)
Flour[d]	UK	Denmark	Nielsen et al. (2003)
Bread[d,e]	UK	Denmark	Nielsen et al. (2003)
Pasta[d]	UK	Italy	Bevilacqua et al. (2007)
Rice[a]	US	US	Bevilacqua et al. (2007)
Sugar (sugar beet)	Europe	Europe	Bevilacqua et al. (2007)
Milk	UK	UK	Williams et al. (2006)
Cream[d]	UK	Denmark	Nielsen et al. (2003)
Butter[d]	UK	Denmark	Nielsen et al. (2003)
Soy beans[a, f]	Brazil	Brazil	Nielsen et al. (2003)
Granule soy	Austria	Austria	SERI (2012)
Tofu	UK	Sweden	Håkansson et al. (2005)
Seitan[g]	UK	UK	Nussinow (1996)
Olive oil	Italy	Italy	Salomone and Loppolo (2012)
Vegetable oil	Europe	Europe	Ecoinvent (2009)
Salt	Europe	Europe	Ecoinvent (2009)
Wine	Australia	Australia	Amienyo et al. (2014)

[a] Where LCA data were not available for the country of origin, the best available data for another country have been used.
[b] Best available data in terms of completeness.
[c] Proxy for prawns.
[d] Data for the processing (data for agriculture are shown separately).
[e] Proxy for bread crumbs.
[f] Component of soy sauce, adapted from a home-made recipe (Forte, 2014).
[g] Adapted from a home-made recipe (Nussinow, 1996).

The most popular ready-made meals in the UK are spread across four cuisines – British, Italian, Indian and Chinese – which together occupy around 85% of the market (Fig. 1). The representative meals within these cuisines have been identified through an online market screening of major supermarkets in the UK. As a results, 13 meal types have been selected, seven from the British and two each from the other three cuisines (Table 1). The reason for a higher number of meals in the British cuisine is that it occupies the greatest market share (Fig. 1) and also because it is the national cuisine. The selected British meals comprise three types of pie (cottage, shepherd's and fisherman's) and four roast dinner options (beef, lamb, pork and chicken). In the Italian cuisine, classic lasagne and spaghetti Bolognese are considered, while the Indian cuisine is represented by two types of curry: chicken korma and lamb masala. Finally, pork and prawns fried rice and chicken noodles have been selected in the Chines cuisine.

Table 5
Utilities used for vegetables pre-processing and meals distribution (adapted from Schmidt Rivera et al., 2014).

Utilities	Vegetables pre-processing [unit/kg]	Meal distribution [unit/meal]
Storage time [h]	12	60
Electricity [Wh]	16.4	52.8
Steam (natural gas) [J]	3.2	–
Water [l]	3.13	–
Refrigerant charge [mg][a]:		
R134a	–	150.7
Ammonia	511.2	180.8
Refrigerant leakage [mg][a]:		
R134a		22.6
Ammonia	76.7	27.1

[a] Ammonia is used in pre-processing facilities and regional distribution centres (RDCp), while retailers use R134a; for both types of refrigerant, the annual leakage rate is 15% (Defra and Brunel University, 2008).

Table 6
Utilities used in the slaughterhouse and seafood processing[a,b].

Utilities (per kg of product)	Cattle	Pigs	Chicken	Fish	Shrimp[c]
Slaughterhouse/ processing[a]					
Input amount for processing [kg]	1.65	1.35	1.374	1.18	3.02
Waste [kg]	0.65	0.35	0.374	0.167	1.98
Electricity [Wh]	39	114	275	272	794
Heat (natural gas) [MJ]	0.17	0.63	0.495	0.22	10.42
Water [l]	2	2.7	12.36	5.3	-
Ammonia [g]	n/a[d]	n/a[d]	n/a[d]	0.12	n/a[d]
Refrigerated storage[b]					
Time [h]	12	12	12	437[e]	437[e]
Electricity [Wh]	0.22	0.22	0.22	1.69[e]	1.69[e]
Ammonia [g]	0.189	0.189	0.189	0.87[e]	0.87[e]
Ammonia leakage [mg]	28.3	28.3	28.3	131[e]	131[e]

[a] Data source for slaughterhouse and fish/seafood processing: Nielsen et al. (2003).
[b] Data source for refrigerated storage, including an annual leakage rate of 15%: Defra and Brunel University (2008).
[c] Shrimp used as a proxy for prawns.
[d] Not available.
[e] Frozen storage. Data source: Schmidt Rivera et al. (2014).

The functional unit is defined as 'a chilled ready-made meal for one person consumed at home in the UK'. The total weight of each meal is 360 g, corresponding to the single serving size typically available on the market. The choice of single-serve meals also reflects the growing number of single-people households who tend to be the main consumers of ready-made meals (BBC, 2013).

The scope of the study is from 'cradle to grave', which includes the production and processing of raw materials, manufacturing of ready-made meals, their distribution and consumption (Fig. 2). Transportation and waste generated across the life cycle are also considered. Each stage is described in more detail in the next section, together with the data and assumptions made in the study.

2.2. Inventory data

2.2.1. Raw materials (ingredients)

The meal recipes and the ingredients are detailed in Table 2. These are based on the average composition across similar meals determined through a market analysis, carried out as part of this research. Where data on the specific ingredients or their proportions were not available, they have been supplemented using the corresponding home-made recipes (BBC, 2014). Due to a large variation in composition of the

Table 7
Energy used in the manufacture of ready-made meals[a].

Cuisine	Ready-made meal	Electricity [kWh/meal]	Fuel oil [l/meal]
British	Cottage pie	0.36	0.04
	Shepherd's pie	0.36	0.04
	Fisherman's pie	0.36	0.04
	Beef roast dinner	0.44	0.05
	Lamb roast dinner	0.44	0.05
	Pork roast dinner	0.53	0.06
	Chicken roast dinner	0.47	0.05
Italian	Classic lasagne	0.40	0.04
	Bolognese spaghetti	0.19	0.02
Indian	Chicken korma curry	0.32	0.04
	Lamb masala curry	0.32	0.04
Chinese	Pork and prawns fried rice	0.19	0.02
	Chicken noodles	0.19	0.02

[a] Estimated based on data for energy consumption in the manufacture of ready-made meals (Schmidt Rivera et al., 2014), cooking times needed for each type of meal (BBC, 2014; Roasting times, 2014) and electricity consumption for ovens and hobs (Jungbluth, 1997).

Table 8
Electricity and water used in the consumption stage (adapted from Schmidt Rivera et al., 2014).

Activity	Electricity [Wh/meal]	Water [l/meal]
Refrigeration[a]	2	–
Microwave[b]	42.3–78.6	–
Washing-up[c]	–	1

[a] Source: Nielsen et al. (2003).
[b] Estimated assuming electricity consumption of 0.0435 MJ/min (Jungbluth, 1997) and the cooking times for individual meals based on manufacturers' cooking instructions (3.5–6.5 min).
[c] Hand washing-up. Source: Defra (2008a, 2008b).

Table 9
Waste generation in different life cycle stages (adapted from Schmidt Rivera et al., 2014).

Stage	Waste generation rate	Source
Pre-processing	15% of vegetables	Milà i Canals et al. (2008)
	27% of chicken[a]	Nielsen et al. (2003)
	26% of pork[a]	Nielsen et al. (2003)
	39.4% of cow and sheep carcass[a]	Nielsen et al. (2003)
Manufacturing	16% of ingredients	BIS (2011)
	0.65% of finished meal	Manufacturer (confidential)
Distribution	2% in each sub-stage	Defra and Brunel University (2008)
Consumption	24% of the meal	WRAP (2009)

[a] Includes offal and leather which are sold to other industries. The impacts have been allocated on an economic basis.

Table 11
Packaging used across the life cycle of the ready-made meals (adapted from Schmidt Rivera et al., 2014).

Life cycle stage	Packaging type	Material	Quantity [g/meal]
Manufacturing	Meal packaging[a]	Polyethylene film	10
		Polyethylene terephthalate	25
Manufacturer/distribution	Box[b]	Cardboard	15
Pre-processing	Crates[c]	Propylene	0.126
Manufacturing/distribution	Euro pallets[d]	Wood	7.56×10^{-3}
Consumption	Plastic bag[e]	Polyethylene	10

[a] Source: Meal manufacturer.
[b] Source: Defra and Brunel University (2008); Packaging calculator (2014). Maximum weight (full): 8 kg, single use.
[c] Source: Defra and Brunel University (2008); Solent Plastic (2013). Crate volume: 26.5 L, used 1000 times.
[d] Source: Defra and Brunel University (2008); Fox's Pallets (2013). Capacity: 750–1000 kg, used 1000 times.
[e] Source: Own measurements of the weight of shopping bags. Single use.

meals found across different brands, the influence of these on the results is also investigated in the study. The details of these variations are shown in Table 3.

Spices, herbs and nuts are not included in the analysis due to a lack of data. These exclusions are not expected to affect the results as each ingredient accounts for <2% of the total mass of a meal. The ingredients for which the data have been available and are considered are listed in Table 4, along with the country of their origin and the sources of LCA data. In cases where LCA data were not available for these countries, the best available data for another country have been used (see Table 4).

Furthermore, for some ingredients, data were not available for all the impact categories considered. For details, see Table S1 in the Supplementary Information (SI).

2.2.2. Pre-processing of ingredients

This is the first step in the manufacturing chain. For the vegetables, it includes cleaning, peeling, chopping, packing (EC, 2010; Milà i Canals et al., 2008) and refrigerated storage in a pre-processing facility (Defra and Brunel University, 2008). For the meat options, pre-processing includes slaughtering (Nielsen et al., 2003) and refrigerated storage. The details of the utilities used for pre-processing of vegetables are presented in Table 5; the data for the slaughterhouse and seafood pre-processing can be found in Table 6. The annual refrigerant leakage is assumed at 15% (Defra and Brunel University, 2008).

2.2.3. Manufacturing and distribution stages

In the manufacturing stage, the ingredients are cooked to make ready-made meals, which are then packed and delivered to a regional distribution centre for products (RDCp). The utilities data have been calculated based on the annual bills and the amounts of ready-made meals produced, both obtained from a manufacturer (confidential). In order to allocate the energy for meal preparation (roasting and cooking) among different meals produced by the manufacturer, home cooking times have been used. The energy data are summarised in Table 7.

Within the distribution stage, the products are stored at the RDCp and then distributed to the retailer. The refrigerant leakage at both the RDCp and retailer is assumed at 15% per year (Defra and Brunel University, 2008). Table 5 provides the data for the consumption of energy, water and refrigerants in the distribution stage.

2.2.4. Consumption

This stage includes car transport of the meal from the retailer to the consumer's home and its refrigeration over 12 h (Schmidt Rivera et al., 2014). The latter only considers the electricity consumption as

Table 10
Distances and transport vehicles considered in the study.

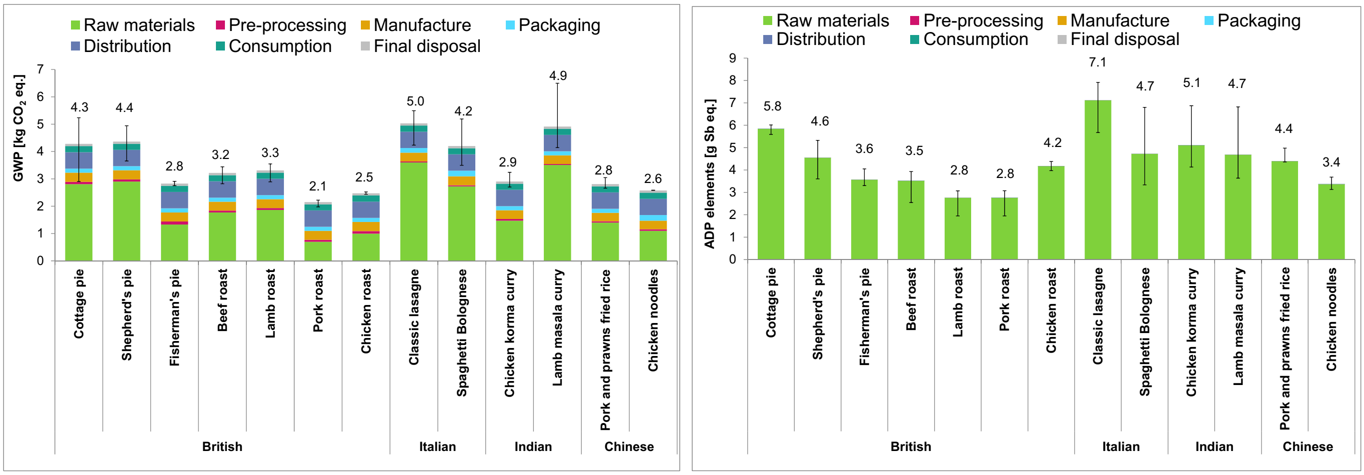
Stage	Distance [km]	Vehicle type	Source
From farm to pre-processing			
In the UK	200	Truck, 32 t	Ecoinvent (2009)
In Europe	1000	Truck, 32 t	Ecoinvent (2009)
In Italy	1720	Truck, 32 t	Ecoinvent (2009)
In Spain	1300	Truck, 32 t	Ecoinvent (2009)
In Brazil	10,000	Transoceanic freight ship	Ecoinvent (2009)
In the US	7000	Transoceanic freight ship	Ecoinvent (2009)
Australia	20,000	Transoceanic freight ship	Ecoinvent (2009)
From pre-processing to manufacturer	100	Truck, 32 t	Ecoinvent (2009)
From manufacturer to RDCp[a]	100	Truck, 32 t	Ecoinvent (2009)
From RDCp to retail	100	Truck, 32 t	Ecoinvent (2009)
From retail to consumer	7.5	Petrol car	Pretty et al. (2005); Ecoinvent (2009)
From consumer to disposal	25	Truck 21 t	Ecoinvent (2009)

[a] Regional distribution centre for products (meals).

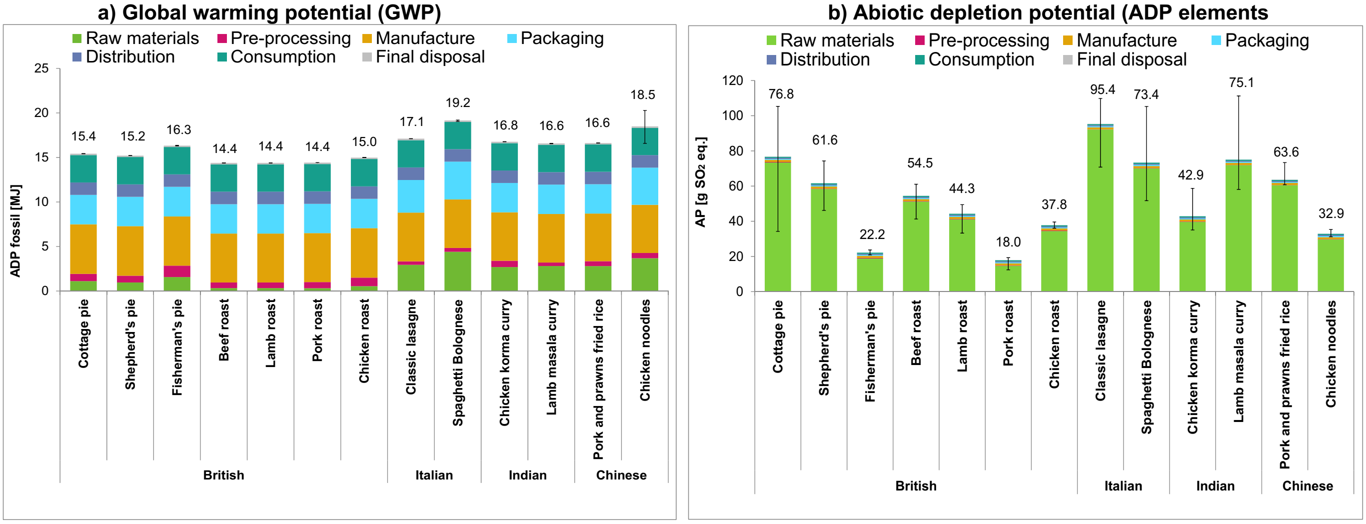
refrigerant leakage from domestic refrigerators is negligible. The meal is cooked in a microwave following manufacturer's instructions on the packaging. The water used for the washing-up of dishes is also considered. The data for the consumption stage can be found in Table 8.

2.2.5. Waste, transport and packaging

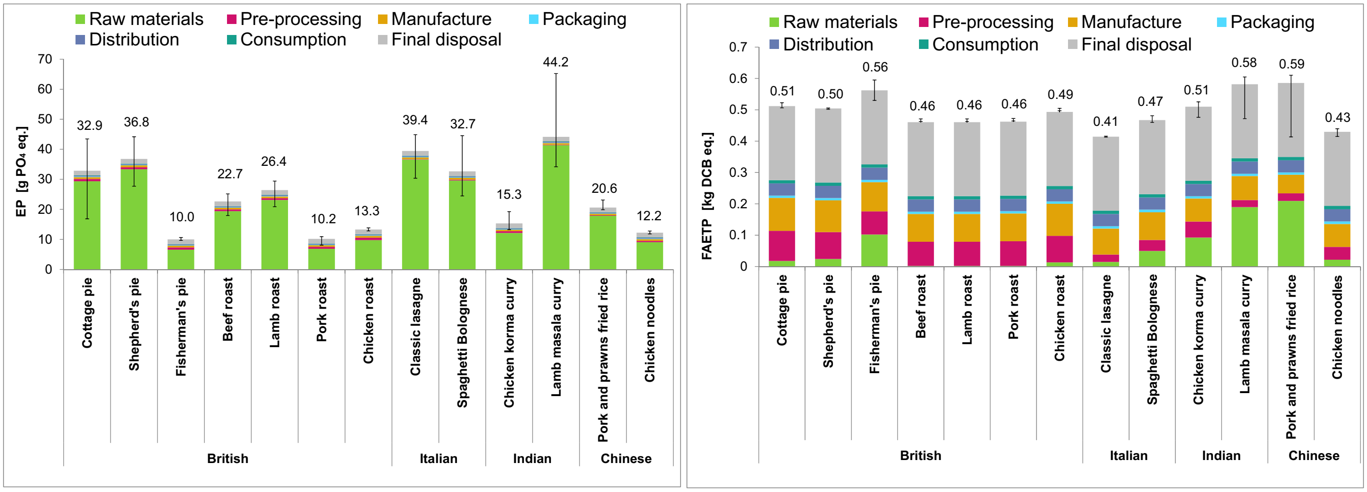
The waste generated in different life cycle stages is specified in Table 9. All waste is assumed to be landfilled and the impacts from landfilling allocated to the stage where the waste is arising. Transport data can be found in Table 10. All vehicles use diesel, except for the



a) Global warming potential (GWP) b) Abiotic depletion potential (ADP elements)

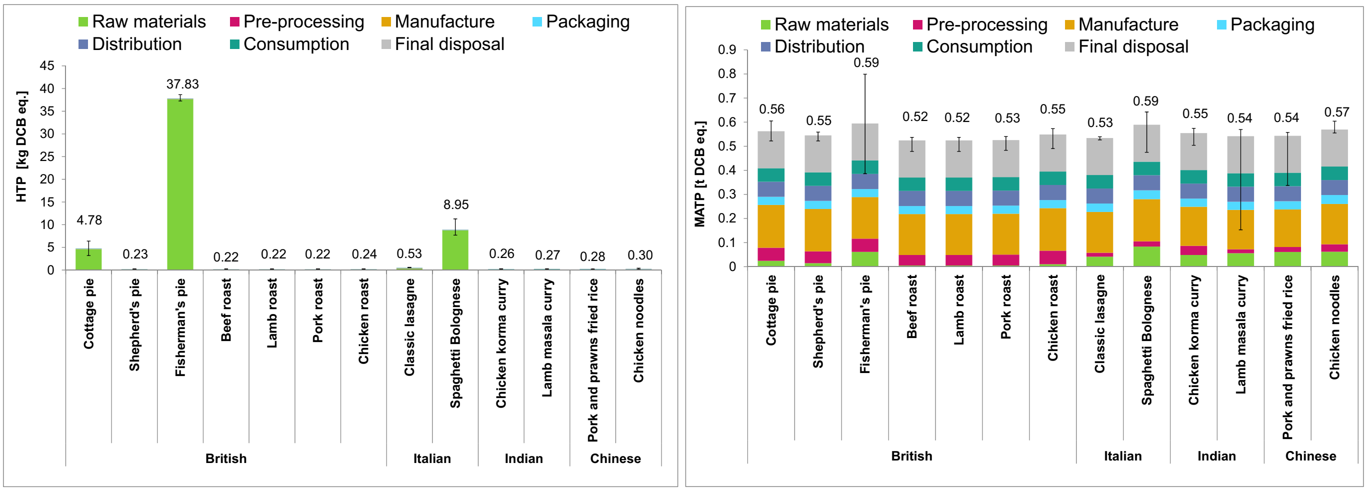


c) Abiotic depletion potential (ADP fossil) d) Acidification potential (AP)



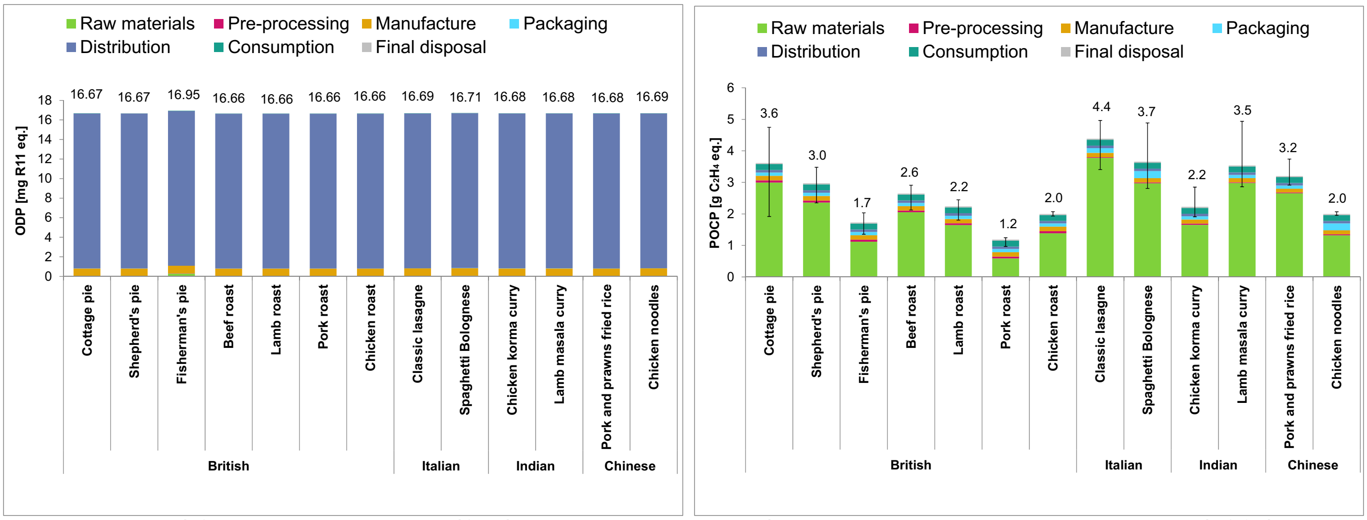
e) Eutrophication potential (EP) f) Freshwater aquatic ecotoxicity potential (FAETP)

Fig. 3. Environmental impacts of ready-made meals and the contribution of different life cycle stages. [Impacts expressed per meal (360 g). The values shown on top of each bar represent the impacts based on the recipes in Table 2. Error bars represent the variation in the meal recipes given in Table 3. Final disposal refers to the waste from the consumption stage; the impacts from the waste in other life cycle stages are included within those stages.]



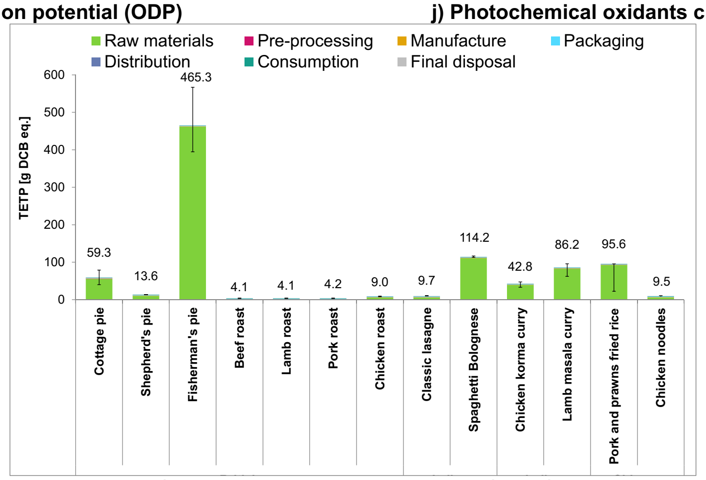
g) Human toxicity potential (HTP)

h) Marine aquatic toxicity potential (MAETP)



i) Ozone depletion potential (ODP)

j) Photochemical oxidants creation potential (POCP)



k) Terrestrial ecotoxicity potential (TETP)

Fig. 3 (*continued*).

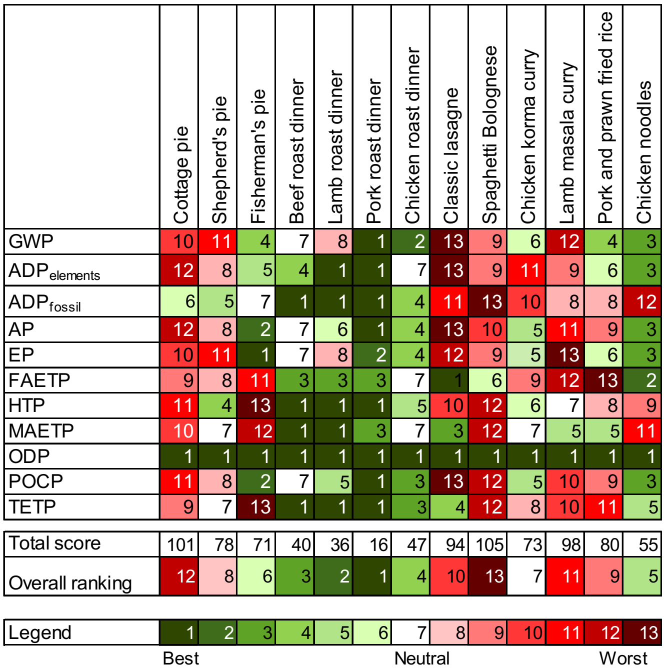
consumer car which uses petrol. All trips include an empty vehicle return. Finally, the data for primary, secondary and tertiary packaging of the raw materials and meals are detailed in Table 11.

2.2.6. Allocation

The energy and water used in pre-processing, regional distribution centres, manufacturing and at the retailer have been allocated on a mass basis. For the animal co-products, economic allocation has been used, based on data from Nielsen et al. (2003) and Williams et al. (2006).

2.3. Impact assessment

The system has been modelled using GaBi software 4.4 (PE International, 2011) and the impacts estimated according to the CML



	Cottage pie	Shepherd's pie	Fisherman's pie	Beef roast dinner	Lamb roast dinner	Pork roast dinner	Chicken roast dinner	Classic lasagne	Spaghetti Bolognese	Chicken korma curry	Lamb masala curry	Pork and prawn fried rice	Chicken noodles
GWP	10	11	4	7	8	1	2	13	9	6	12	4	3
$ADP_{elements}$	12	8	5	4	1	1	7	13	9	11	9	6	3
ADP_{fossil}	6	5	7	1	1	1	4	11	13	10	8	8	12
AP	12	8	2	7	6	1	4	13	10	5	11	9	3
EP	10	11	1	7	8	2	4	12	9	5	13	6	3
FAETP	9	8	11	3	3	3	7	1	6	9	12	13	2
HTP	11	4	13	1	1	1	5	10	12	6	7	8	9
MAETP	10	7	12	1	1	3	7	3	12	7	5	5	11
ODP	1	1	1	1	1	1	1	1	1	1	1	1	1
POCP	11	8	2	7	5	1	3	13	12	5	10	9	3
TETP	9	7	13	1	1	1	3	4	12	8	10	11	5
Total score	101	78	71	40	36	16	47	94	105	73	98	80	55
Overall ranking	12	8	6	3	2	1	4	10	13	7	11	9	5

Legend	1	2	3	4	5	6	7	8	9	10	11	12	13
	Best						Neutral						Worst

Fig. 4. Ranking of the ready-made meals based on their environmental impacts [For the impacts nomenclature, see Fig. 3. Total score for each meal represents the sum of its scores for each impact, assuming an equal weighting of all impacts. The overall ranking is based on the total score, with the lowest score representing the best option and the highest the worst.]

2001 impact assessment method (Guinée et al., 2002). The following 11 environmental impacts are considered: global warming potential (GWP), abiotic depletion potential of elements ($ADP_{elements}$) and fossil fuels (ADP_{fossil}), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), photochemical oxidation potential (POPT), ozone depletion potential (ODP) and terrestrial ecotoxicity (TETP). For GWP, biogenic carbon and land use change have not been considered.

3. Results and discussion

This section discusses first the environmental impacts of different meals considered in the study. This is followed by an analysis of the influence on the impacts of meal recipes, including the effect of using meat replacements from non-animal sources. The final section considers the impacts of annual consumption of ready-made meals in the UK.

3.1. Environmental impacts of ready-made meals

Fig. 3a–k shows the estimated environmental impacts of the 13 ready-made meals for the 11 impact categories considered. The results indicate that environmentally the most sustainable options are the roast dinners, and in particular the pork-based meal. Lasagne, spaghetti, lamb masala curry and cottage pie have generally the highest impacts. The main hotspots across the meals are the raw materials (>50%), distribution (14%) and manufacturing (12%) stages. It should be noted that data for some impacts of the raw materials were not available (see Table S1) and hence these may be underestimated. Further discussion of each impact per meal is provided below.

3.1.1. Global warming potential

As can be seen in Fig. 3a, the GWP ranges from 2.1 kg CO_2 eq. for the pork roast dinner to 5 kg CO_2 eq. for the lasagne. Chicken roast is the second best option with 2.5 kg CO_2 eq. while the cottage and shepherd's pies as well as the spaghetti trail closely behind the lasagne with GWP raging from 4.2 to 4.4 kg CO_2 eq. per meal.

The raw materials are the main hotspot for GWP, contributing on average 55% across the meals, followed by distribution (19%), manufacturing (10%), consumption (7%) and packaging (5%). The contribution of final disposal and pre-processing is small (2%–3%). However, the contributions vary significantly with the type of meal. For example, the raw materials cause ~70% of the GWP of lamb masala curry and lasagne. For the former, this is due to the lamb, which accounts for 91% of the impact from this stage. For the lasagne, beef is the main contributor with 83%, followed by butter with 10%. Similarly, for the cottage and shepherd's pies and spaghetti, the ingredients contribute ~65% of the GWP, with the meat (beef and lamb) being responsible for ~90% across the three meals.

For the chicken curry, pork and prawns fried rice and beef and lamb roasts, the ingredients cause half of their respective impact. For the first two meals, the meat is the main contributor with almost 60%. In the case of curry, the rest of the impact comes from cream (30%) and rice (10%), while for the fried rice, rice and eggs contribute around 15% each. The impact of the beef and lamb dinners is largely determined by the meat (~90%), with the remaining impact being due to the eggs (in Yorkshire pudding) and potatoes.

Finally, for fisherman's pie, chicken roast and chicken noodles, the raw materials cause around 43% of the impact from these meals. The main contributor for the former is butter (58%), followed by prawns (15%). Chicken is the main hotspot for both the roast dinner and chicken noodles, contributing 84% and 66% to the GWP from the raw materials stage. For the latter, the noodles cause 28% of the impact related to the ingredients, while soy beans in the soy sauce contribute only 3%.

3.1.2. Abiotic depletion potential of elements and fossil fuels

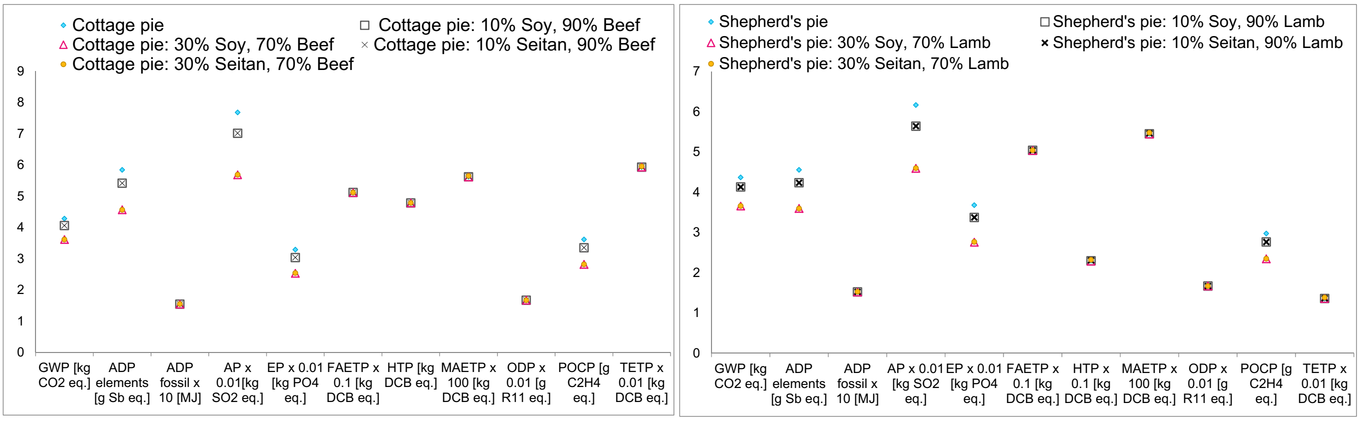
The highest $ADP_{elements}$ is estimated for the lasagne (2.8 g Sb eq.) and the lowest for the lamb and pork roasts (7.1 g Sb eq.); see Fig. 3b. The ingredients are the single largest contributor to this impact across the meals (99%), mainly due to the animal-derived products. Specifically, beef and eggs have the highest $ADP_{elements}$ with 36 and 38 kg Sb eq./t carcass (Williams et al., 2006) while, for example, the impact from potatoes is 0.9 kg Sb eq./t. The main reason for such high values is the resources used to produce fertilisers and pesticides for growing the feed for cows and chickens.

Spaghetti Bolognese is the worst option for ADP_{fossil} (19.15 MJ) while the roast dinners are the best alternatives (<15 MJ; Fig. 3c). The manufacturing and packaging stages are the main contributors to this impact, adding on average across the meals 34% and 22%, respectively. This is due to the energy consumed to produce the meals and the use of petroleum feedstock for plastic packaging. The third contributor is the consumption stage with 19% on average. The contribution of raw materials ranges from 2% to 20%, depending on the meal. The impact from this stage is related to energy requirements for processing the ingredients, such as pasta, tomato paste and flour.

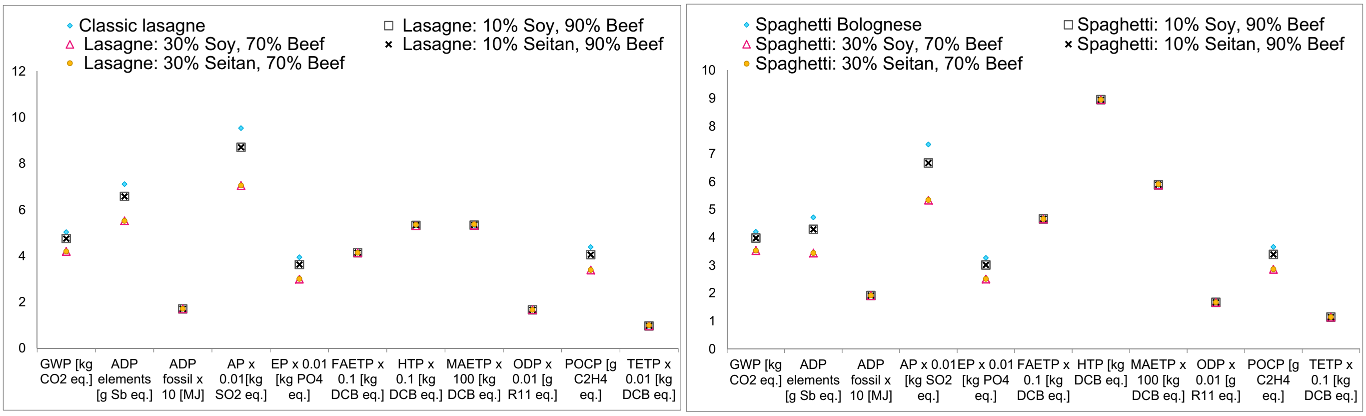
3.1.3. Acidification and eutrophication potentials

As shown in Fig. 3d, the pork roast has the lowest acidification potential (18 g SO_2 eq.), followed by fisherman's pie (22 g); the lasagne is the worst option at 95.4 g SO_2 eq. The first two are also the best options for eutrophication (10 g PO_4 eq.) while lamb masala curry has the highest impact (44.2 g PO_4 eq.), followed by the lasagne (39 g PO_4 eq.).

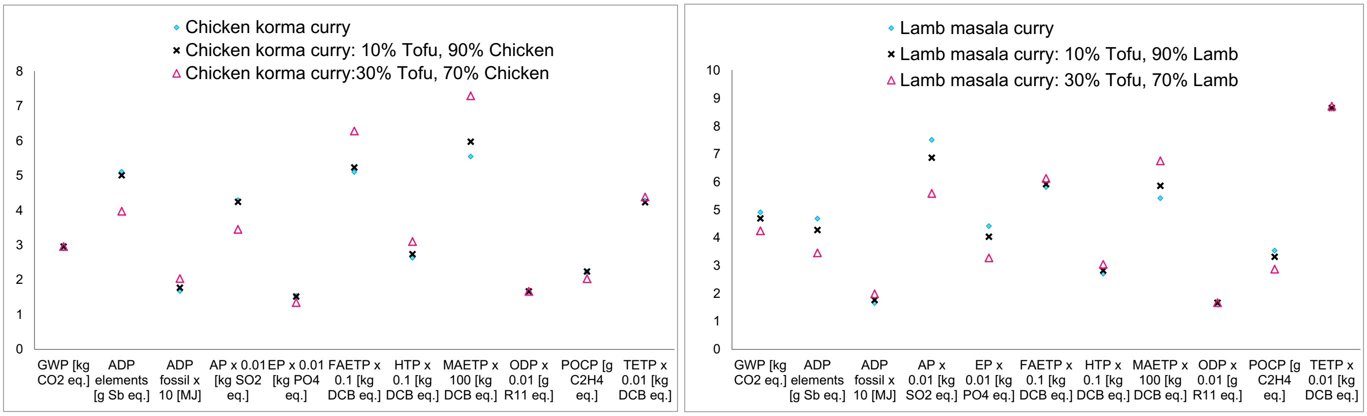
For both impacts, the ingredients are the main hotspot, contributing on average 90% to acidification and 83% to eutrophication (Fig. 3e). The cultivation of vegetables and animal feed causes the majority of the impacts, mainly due to the emissions associated with the use of mineral fertilisers and manure.



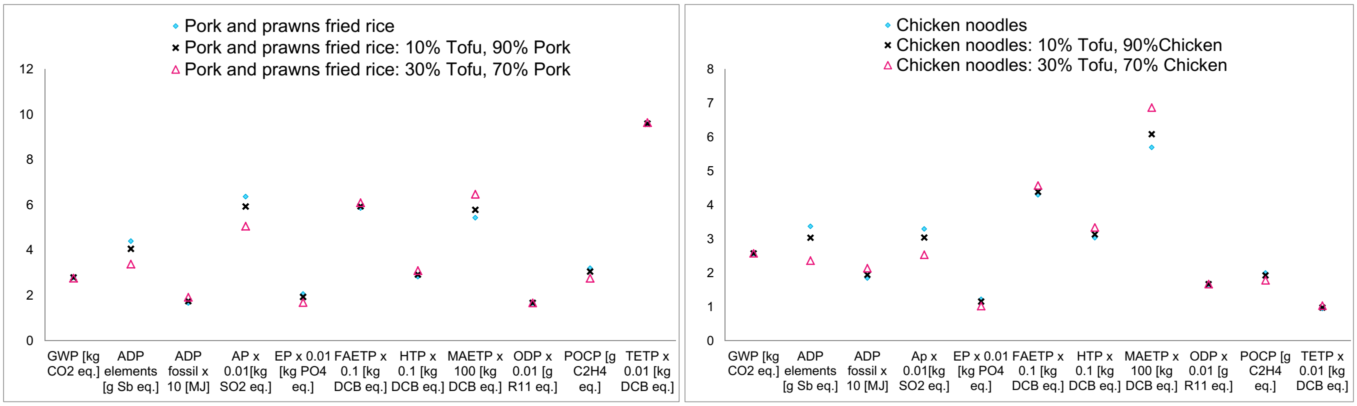
a) Cottage pie **b) Shepherd's pie**



c) Classic lasagne **d) Spaghetti Bolognese**



e) Chicken korma curry **f) Lamb masala curry**



g) Pork and prawns fried rice **h) Chicken noodles**

Fig. 5. Influence of different meat replacement options on the environmental impacts of ready-made meals. [All impacts expressed per one meal (360 g). For the recipes, see Table 2 and Table 3. For the impacts nomenclature, see Fig. 3. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown on the x-axis for relevant impacts.]

Table 12
Variables considered in the Monte Carlo simulation.

Variables	Min	Max
Energy used in the pre-processing stage[a]	−20%	+20%
Energy used in the distribution stage[a]	−20%	+20%
GWP of meat products[b] [kg CO_2 eq./kg]		
Beef	12.37	37.92
Lamb	11.04	43.17
Pork	3.50	6.97
Chicken	1.06	9.98

[a] For the base-case values, see Table 5.
[b] Sourced from Clune et al. (2017).

3.1.4. Freshwater aquatic ecotoxicity

For this impact, the differences between the meal options are less pronounced than for most others, ranging from 0.41 (lasagne) to 0.59 kg DCB eq. (fried rice; see Fig. 3f). The main contributor is the disposal of post-consumer waste (48% on average), mainly due to the emissions from food-waste landfilling. The manufacture of meals adds a further 18%, also due to the food waste and packaging landfill. The contribution of raw materials is relatively small (8%), with the rest of the impact being from pre-processing (12%) and distribution (10%).

3.1.5. Human ecotoxicity potential

The highest HTP is found for the fisherman's pie (37.8 kg dichlorobenzene (DCB) eq.), followed by spaghetti (8.9 kg DCB eq.) and cottage pie (4.8 kg DCB eq.). All other meals have a much lower impact, ranging from 0.22 to 0.58 kg DCB eq. The main reason for the high impact of these three meals is the raw materials (Fig. 3g) – for the fisherman's pie, it is the fish while for spaghetti Bolognese and the cottage pie, it is the wine and olive oil.

3.1.6. Marine aquatic ecotoxicity potential

Like FAETP, this impact is similar across the meal options, ranging from 0.52 t DCB eq. (beef and lamb roasts) to 0.59 t DCB eq. (fisherman's pie and spaghetti). The main contributors are manufacturing (31% on average) and post-consumer waste disposal (28%). For the former, the main cause of the impact is the inorganic air emissions from electricity generation. Emissions from landfilling are the main contributors to MAETP from post-consumer waste disposal. The distribution and consumption stages add on average 21% to the total, mainly due to the emissions from electricity. Finally, pre-processing, packaging and raw materials contribute on average 7% each.

3.1.7. Ozone depletion potential

This impact is almost the same across the meals (Fig. 3i) because the main contributor is the distribution stage (95%), which is identical for all the options. Specifically, this is due to the use of R134 in the retail stage. The manufacturing stage contributes the remaining 5%.

3.1.8. Photochemical oxidants creation potential

Fig. 3j shows that the lowest POCP (1.2 g C_2H_4 eq.) is estimated for the pork roast and the highest for the lasagne (4.4 g C_2H_4 eq.). The main contributor to this impact is again the ingredients, ranging from 50% for the pork dinner to 86% for the lasagne. The contribution of the other stages is below 10%: manufacturing and consumption contribute on average 6% and 8%, respectively, and the packaging 5%.

3.1.9. Terrestrial ecotoxicity potential

The fisherman's pie has by far the highest TETP, estimated at 465.3 g DCB eq. This is four times higher than for the spaghetti, the meal with the second highest impact (Fig. 3k). The best options are the beef, lamb and pork roasts (~4 g DCB eq.) while the impact from the chicken dinner is more than twice as high. The latter is due to the recipes, as the chicken roast includes a higher amount of meat and oil (see Table 2).

The main contributor to most meals is the raw materials stage, ranging from 60% (shepherd's pie, chicken roast, lasagne and noodles) to 99% for most of the others. The exceptions are beef, lamb and pork roasts, where the ingredients contribute only 10%. The key ingredients are wine, olive oil and fish, but this may be due to the lack of data for some other ingredients (see Table S1). The manufacturing and packaging stages contribute on average 10% each, while consumption adds 7%.

The above findings are summarised in a ‘heat map’ in Fig. 4, ranking the meal options with respect to their environmental impacts. If all the impacts are equally weighted, overall the best meal types are the roast dinners, with the pork option being ranked top. The least environmentally sustainable option is spaghetti Bolognese, followed by the cottage pie, lamb curry masala and lasagne.

3.2. Influence of recipes

As detailed in Table 3, the composition of each type of meal available on the market varies significantly, depending on manufacturers' recipes. Therefore, this section explores how the variations in the recipes affect the environmental impacts of each meal.

As seen in Table 3, the main variations in the recipes are related to the amount of rice, pasta, vegetables and mashed potato, as well as to the ratio between the meat and sauce/gravy. The highest recipe variation for the latter is found for cottage pie and the curries, followed by spaghetti, lasagne and fisherman's pie. The results in Fig. 3, shown as error bars, indicate that the recipe variations affect most impacts significantly.

The highest variations in GWP (22%–32%) are found for the cottage pie, spaghetti and lamb curry. The variations at the top end of the range position lamb curry as the worst option for this impact (6.5 kg CO_2 eq.). Likewise, recipe variations also reduce the GWP, with the greatest reduction found for the cottage pie (32%), followed by the shepherd's pie, lasagne, spaghetti and lamb curry (~16%). Nevertheless, the pork roast still remains the best option for GWP.

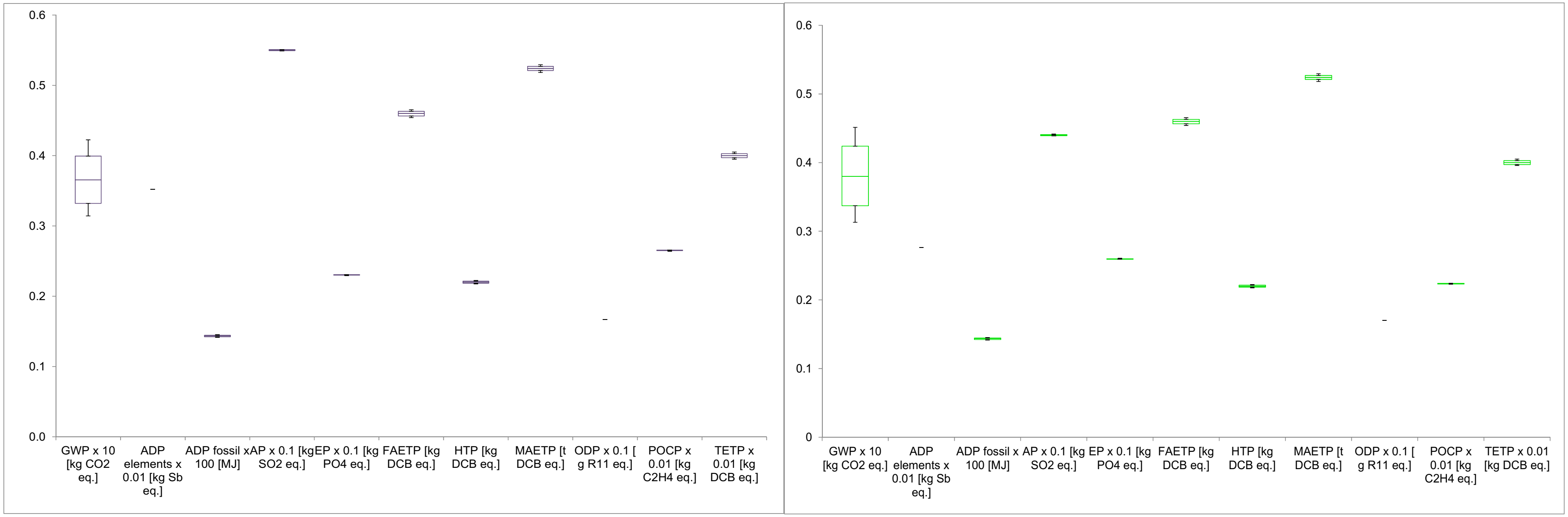
In the case of $ADP_{elements}$, spaghetti, lasagne and the curries are most affected by the recipe variations, which increases by 35%–45% or decreases by 19%–29%, depending on the recipe. This leads to some overlapping ranges between these three products (Fig. 3b). However, at the top range, lasagne still has the highest impact (7.9 g Sb eq.).

Similarly, the greatest variations in AP (−23% to 48%) and EP (−49% to 48%) can be observed for the lamb curry, spaghetti and cottage pie because these two impacts are mainly affected by the type of meat and its contribution to the recipe. For the maximum increase in the impacts, lamb curry becomes the worst option, with 111.3 g SO_2 eq. and 65.2 g PO_4 eq., respectively. Overall, pork roast still has the lowest impacts across the variations considered.

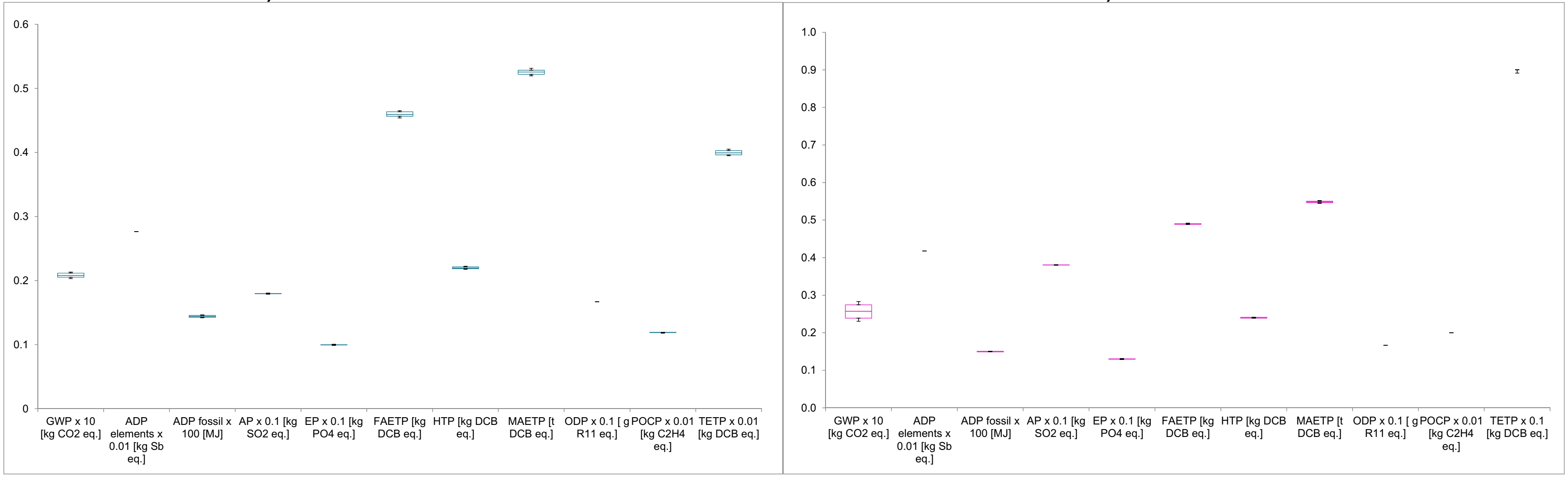
The cottage pie and spaghetti also show the highest variations in HTP and POCP. The variations in the cottage pie recipe change both impacts by almost a half; for the spaghetti, the change is ~35%. However, these changes do not affect the ranking order of the meals with respect to these two impacts.

FAETP is only affected significantly for lamb curry and pork and prawn fried rice, with the impact reducing by 23% and 37%, respectively. This makes pork and prawn fried rice the best option for this impact across the recipe variations considered, overtaking the previously best meal, lasagne. The increase in the impact for these two meals with the recipe variations is small (4%).

For MAETP, the greatest variation is seen for the fisherman's pie (−55% to 26%), mainly due to the change in the amount of fish and prawns. At its maximum value, the impact is 35% higher than for the best options in the base case (meat roasts). An even greater change is seen for the MAETP of lamb curry, which decreases by around three times, making it the best meal across the recipe variations. Pork and prawn fried rice also see a significant reduction (63%) in the impact,



a) Beef roast dinner **b) Lamb roast dinner**



c) Pork roast dinner **d) Chicken roast dinner**

Fig. 6. Uncertainty analysis for four roast dinner meals. [The boxes denote the median and the 25th and 75th percentile values while the whiskers represent the 10th and 90th percentiles. For the impacts nomenclature, see Fig. 3. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown on the x-axis for relevant impacts.]

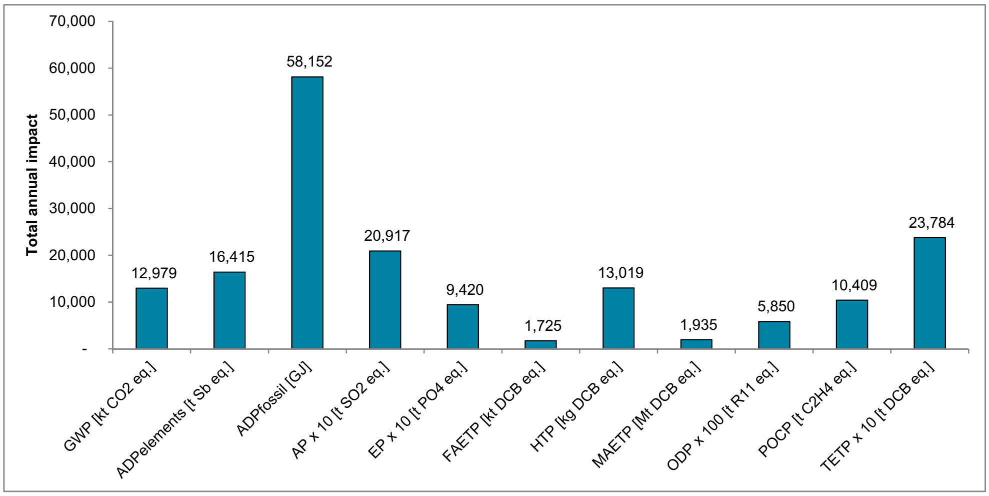


Fig. 7. Environmental impacts of ready-made meals consumed annually in the UK. [All impacts expressed per year. For the impacts nomenclature, see Fig. 3. Some impacts have been scaled. To obtain the original values, multiply with the factor on the x-axis where relevant.]

positioning it the second best meal, after the lamb curry. TETP is also most affected for the fisherman's pie and pork and prawn fried rice; however, there is little change in the ranking order of the meals.

Only two impacts are largely unaffected by the recipe variations: ADP_{fossil} and ODP. The former is determined by energy consumption (manufacturing and packaging), which in this study does not depend greatly on ingredients, while the ODP depends mainly on the refrigerant use (distribution stage). However, ADP_{fossil} of chicken noodles shows some variation (±10%), due to a variation in the amount of noodles, which affects energy requirements in their production process.

3.3. Influence of meat replacements

Due to the importance of meat for the impacts of the meals, this section analyses environmental implications of substituting a proportion of meat with meat-replacement options. The following options are considered: soy granules (SERI, 2012), seitan (VRG, 2014) and tofu (Håkansson et al., 2005). A modest replacement of 10%–30% (by mass) of meat is assumed to maintain the taste and visual appearance of the meals.

For the cottage and shepherd's pies, the meat replacements considered are the soy granules and seitan because these meals contain minced meat, which is easier to replace without changing significantly the appearance of the original recipe. For that reason, meat replacements are not considered for the fisherman's pie and roast dinners. The results in Fig. 5a & b indicate that five impacts from the cottage and shepherd's pies reduce by up to 26% with the meat replacements (GWP, $ADP_{elements}$, AP, EP and POCP). For the cottage pie, the GWP decreases by 16% to 3.6 kg CO_2 eq. while the other four impacts reduce by 22%–26%. The improvements for the shepherd's pie are the largest for AP and EP (~25%), with the GWP decreasing by 16% to match the impact from the cottage pie. The remaining impacts are largely unaffected.

Soy granules and seitan are also considered for the lasagne and spaghetti. Fig. 5c & d show that both meals are similarly affected by these meat replacements, which reduce the same five impacts as above by up to 27%, with the GWP being 17% lower.

Tofu has been assumed as a meat replacement in the curries because of its similarities in terms of consistency and appearance with diced meat. Fig. 5e & f show a reduction in four impacts ($ADP_{element}$, AP, EP and POCP) of 22%–26%. However, the meat replacement also increases four other impacts (ADP_{fossil}, FAETP, MAETP and HTP) by 25%–32%. GWP exhibits a different trend: for the chicken korma, the higher energy use in the tofu-making process increases the impact slightly (2%), while for the lamb masala, tofu improves the GWP by up to 14%.

Following the same rationale as above, tofu has been selected as a meat replacement for chicken noodles and pork and prawns fried rice. As shown in Fig. 5g & h, the impacts of these meals are affected similarly: the use of tofu decreases four impacts ($ADP_{element}$, AP, EP and POCP) by 23%–30%, while increasing four others (ADP_{fossil}, FAETP, HTP and MAETP) by up to 21%. The GWP is largely unaffected.

It should be noted, however, that LCA data for these meat replacements are incomplete (Table S1). Therefore, these results should be considered in that context. Furthermore, other quality parameters, such as texture, taste and nutritional content, as well as public acceptance, should be evaluated alongside the environmental impacts. Nevertheless, vegetarian protein sources have been promoted as not only more sustainable but also healthier options than meat (Bohrer, 2017; Neacsu et al., 2017; Van Mierlo et al., 2017), which could help to expand the market and reduce health impacts associated with ready-made meals (*Kanzler* et al., 2015).

3.4. Uncertainty analysis

This section considers the uncertainty in the results, focusing on the parameters which affect the impacts and for which the data either vary significantly or are uncertain. A Monte Carlo (MC) simulation has been performed for these purposes using GaBi software and assuming a uniform distribution. The four roast dinner meals – beef, lamb, pork and chicken – have been selected as illustrative examples to estimate the levels of uncertainty related to the following parameters: GWP of different types of meat and energy used in the pre-processing and distribution stages (Table 12). No other impacts from meat are considered due to a lack of data. The effect of other parameters, such as the consumption of energy in meals manufacturing and the amount of refrigerant used across the supply chain is not included here as this was explored previously for the case of chicken roast in Schmidt Rivera et al. (2014).

The results are presented in Fig. 6a–d and Tables S2–5 in the SI. As can be seen, the highest variation in the results is found for the GWP of the beef (+16% for the 90th and − 14% for the 10th percentiles) and lamb dinners (±19%), with the variations for the chicken (±10%) and pork (±3%) meals being more modest. On the other hand, the effect of the energy used in the pre-processing and distribution stages is negligible, with the highest variation of ±2% found for ADP_{fossil}.

3.5. Environmental impacts from annual consumption of meals in the UK

As mentioned in the introduction, the UK ready-made meals sector is the second largest market in the world, with the annual per-capita consumption of 19 kg (Statista, 2018). This means that UK consumers eat around 1,261,600 t of ready-made meals per year. This section discusses the total impacts associated with this level of consumption.

As there are no data on the sales of individual meals within different cuisines, the estimates have been carried out as follows. First, the impacts of the meals have been averaged within each of the four cuisines considered to estimate an average impact of each cuisine per kg of meal. These values have then been weighted using the market share of each cuisine related to the annual sales volume of meals in each cuisine (see Fig. 1). The impacts of other cuisines, which represent 15% of the market share, are not known. Therefore, to capture the full impacts of the ready-made meals sector, the cumulative share of the four cuisines considered in this work (85%) has been scaled up to 100%, with each cuisine scaled up in proportion to its current share. The assumption made in the scaling-up process is that the impacts of other cuisines lie within the ranges of the four main cuisines. Finally, the estimated average weighted impacts of each cuisine have been summed up to obtain the total average weighted impact across all the four cuisines (and by implication, of all other cuisines). An example estimate can be found for GWP in Table S6 in the SI.

The results are shown in Fig. 7. Although the whole range of impacts is shown in the figure, the discussion here focuses on GWP. The reason for that is the difficulty in contextualising the other impacts at the sectoral or national levels as these estimates are not available for any of the categories apart from GWP.

As can be seen in Fig. 7, total GWP is estimated at 12.98 Mt. CO_2 eq./yr, equivalent to the annual GHG emissions of a country such as Jamaica (Joint Research Centre, 2014). This also represents 15.7% of total GHG emissions from the food and drink sector. This contribution is based on an estimate of consumption-based GHG emissions in the UK of 550 Mt. CO_2 eq. per year, 15% of which (82.5 Mt. CO_2 eq.) is due to the food and drink sector (Druckman and Jackson, 2009).

Another way to contextualise these results is to consider the carbon budgets. To ensure that the increase in the average global temperature does not exceed 2 °C, the target set by the Paris Agreement (UNFCCC, 2015), the annual budget related to food intake should not exceed 2365 kg CO_2 eq. per person (Ritchie et al., 2018). With an average of 10.9 kg CO_2 eq. per kg of ready-made meals (see Table S6) and 19 kg of meals consumed per capita, the annual consumption of ready-made meals leads to carbon emissions of 195.5 kg CO_2 eq. per person. This represents 8% of the total per-capita carbon budget related to food. For a more stringent target of the global temperature increase not exceeding 1.5 °C, the food intake budget corresponds to 1337 kg CO_2 eq. per person per year (Ritchie et al., 2018), in which case the consumption of ready-made meals in the UK would contribute 15% to the total food-related carbon budget.

Therefore, the ready-made meals contribute significantly to the overall GHG emissions, both in the food sector and to per-capita carbon budgets. Hence, exploring the use of meat replacements and the development of recipes with low-carbon ingredients will be key for reducing GHG emissions and some other impacts associated with these products. Although it appears that the population's interest in home-cooking is increasing (BBC, 2016; GlobalData, 2018), market reports are still confident in further growth of the ready-made meals market (Statista, 2018). Additionally, the fast-growing uptake of these products in countries such as India, China and Japan (Statista, 2018), suggests that the environmental impacts of ready-made meals will continue to increase globally unless appropriate measures are taken to reduce them.

4. Conclusions

This study has estimated for the first time the environmental impacts of a range of ready-made meals available on the UK market in four most popular cuisines: British, Italian, Chinese and Indian. The results suggest that environmentally the most sustainable options are the roast dinners and, in particular, the pork option. The highest impacts are found for spaghetti Bolognese, lasagne, lamb masala curry and cottage pie. The impacts vary significantly across the meals. For instance, the global warming potential ranges from 2.1 kg CO_2 eq. (pork roast) to 5 kg CO_2 eq. (lasagne). Recipes for the same type of meal vary considerably among the producers, which affects most impacts significantly as the ingredients contribute >50%. However, the ranking of the best and worst options is largely unaffected by the variations in the recipes. In addition to the ingredients, the other most contributing stages are distribution and manufacturing of meals, with an average across the meals of around 13% each.

The results also indicate that replacing meat with soy and seitan would reduce five out of 11 impacts by up to 27%, including global warming potential. Using tofu instead of meat has a mixed effect: it reduces four impacts by up to 26%, including global warming potential, but also increases other four categories by up to 32%.

Annual consumption of ready-made meals in the UK generates 12.98 Mt. CO_2 eq. This contributes almost 16% to the total GHG emissions from the food and drink sector. It also represents 8% of the total per-capita food carbon budget for the climate target of 2 °C; this goes up to 15% for the more stringent target of 1.5 °C. Therefore, the ready-made meals contribute significantly to the GHG emissions, both in the food sector and to personal carbon budgets. Hence, exploring the use of meat replacements and the development of environmentally less intensive recipes will be key for reducing the impacts associated with these products. Otherwise, with the expected growth in consumption of these products in countries such as India, China and Japan, the environmental impacts of ready-made meals will continue to increase worldwide.

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Appendix A. Supplementary data

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