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Environmental sustainability assessment of ready-made baby foods: meals, menus and diets

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Abstract

Although there is a growing body of literature on the environmental impacts of food, virtually none of the studies has addressed baby foods. Therefore, this work explored the life cycle environmental impacts of different ready-made baby foods, both at the level of individual meals and their combinations within a weekly menu. Twelve different meals were considered, based on baby food products available on the UK market, spanning breakfast, lunch and dessert. Menus following four different diets – omnivorous, vegetarian, pescatarian and dairy-free – were also evaluated. The results showed that, on average, lunch meals had the highest impacts and desserts the lowest. Breakfast has either intermediate (wet porridge) or low (dry porridge) impacts. Among the lunch meals, spaghetti Bolognese and salmon risotto had the highest impacts and among the desserts, strawberry, raspberry and banana as well as apple, pear and banana purees had the lowest. The key hotspots across the meals were raw materials and packaging. Meals with more meat and cream were found to have higher impacts. Manufacturing also played a significant role for global warming potential as well as depletion of fossil resources and the ozone layer due to the fossil fuels used in the process. When the impacts were analysed per mass of baby food consumed weekly, the dairy-free diet had higher impacts than the other three, but the difference among them was relatively small. The trends changed when nutritional value was taken into account, with the dairy-free diet exhibiting considerably higher impacts per unit of energy content. In that case, the pescatarian diet became the best option for most impacts. There was little difference between the omnivore and vegetarian diets. It is expected that these results will be of interest to baby food manufacturers and consumers, helping them to make more informed manufacturing and purchasing decisions.

Keywords: climate change; convenience food; environmental impacts; infants; life cycle assessment

1 Introduction

It is widely acknowledged that food production and consumption are significant contributors to a range of environmental, social and economic sustainability issues. For example, they account for 80% of global water consumption (Molden et al. 2010) and 30% of energy used worldwide (FAO 2011). Impacts vary across the food supply chain. For instance, agriculture is responsible for up to 25% of global greenhouse gas emissions (Vermeulen et al., 2012). In Europe, the food and drink industry consumes 5.3% of the global industrial energy use and 1.8% of the total water use in the region (Food Drink Europe, 2012). In the UK, food transportation accounts for 19 Mt CO₂ eq. (Vermeulen et al., 2012), while the retailers produce 4 Mt CO₂ eq. (Tassou et al. 2011). Globally, a third of the food produced is wasted, which generates 3.3 Gt CO₂ eq. (FAO, 2013).

With the global population expected to reach 9.1 billion in 2050, the Food and Agriculture Organisation (FAO) estimates that food production should increase by 70% (FAO 2009). Hence, unless the current food production and consumption undergo significant transformation, environmental impacts will only increase in future. For instance, a 50% increase in global food production by 2030 is expected to increase the energy demand by 45% and water consumption by 30% (Beddington 2008).

In addition to environmental issues, food production and consumption also have major implications for society and the economy. Changes in food consumption are affecting negatively the health of the population in Europe (EUPHA 2017), as poor diets are linked to the increase in diet-related chronic diseases (DRCD). This trend is also seen globally, with 40% of deaths related to DRCD (Candari et al. 2017). It has also been estimated that the direct and indirect costs to the health system related to poor diets account for 0.5% of the national income in Europe (Candari et al. 2017). For example, even 20 years ago, the total external costs of UK agriculture were estimated at £2.34 billion per year (Pretty et al. 2005). Estimates have also suggested that potential avoided health expenditure of £20 billion per annum could be achieved in the UK if the population followed national nutritional guidelines (Cabinet Office 2008).

Consequently, diet is closely linked to sustainability. The environmental sustainability of diets has already been demonstrated to vary with the food group (Barilla Center 2010). For example, according to Notarnicola et al. (2017), meat and dairy products have the highest environmental impacts of food consumption in Europe. Hallström et al. (2015) also showed that the climate change impact of a reduced-meat diet depends on which foods substitute meat and that there is a research gap on consumption patterns of specific groups in the population. On the other hand, Tukker et al. (2011) suggest that “moderate diet changes are not enough to reduce impacts from food consumption drastically”.

In the UK, one of the priorities of the Food 2030 strategy is focused around enabling and encouraging sustainable diets. Although measuring the environmental footprint of food products tends to focus on single issues, such as carbon footprint, there is a need for broader environmental assessments of what we choose to eat (HM Government 2010), considering the full life cycle of food. Given that food production involves a complex chain of activities from agriculture to processing, packaging and consumption, as well as a global network of transportation between each stage, it is rarely clear to consumers or producers how best to reduce their overall impacts. For this reason, life cycle assessment (LCA) is an invaluable tool, as it can be used to analyse a broad range of environmental impacts from ‘cradle to grave’, encompassing all of the above stages. Furthermore, by helping to identify the key contributors to each impact, improvement opportunities can be targeted more effectively.

There are numerous LCA studies of food. However, most have focused on individual food items or ingredients, rather than whole meals, menus or diets. An example of a whole-meal study is that by Schmidt Rivera et al. (2014), which estimated a range of impacts of a ready-made chicken roast dinner in comparison to the equivalent home-made meal. Another study (Berlin and Sund 2010) considered two meals – pork and chicken-based – but focused on four impacts only: primary energy demand, global warming potential, acidification and eutrophication. Furthermore, Saarinen et al. (2012) compared six types of home and ready-made school lunches, estimating only global warming potential and eutrophication. School meals were also the topic of the study by Benvenuti et al. (2016), which went beyond individual meals to determine the global warming potential and water consumption in the life cycle of a lunch menu. Studies of different diets are scarce and include consideration of environmental impacts of the Dutch and Mediterranean diets (van Dooreen 2014; Castañé and Antón 2017).

However, regardless of the rapid growth of the baby food sector, there is little information on the environmental sustainability of baby food. To our knowledge, there are only three publications available so far. Two of these were carried out in Sweden 20 years ago (Mattsson 1999a; b) and considered porridge and carrot puree. The hotspots for the former were found to be agriculture and food processing, primarily due to the impacts of milk production, pesticides used for the feed production and fossil fuels used in processing. For the carrot puree, where organic and integrated farming were compared, the organic system

was found to have significantly higher acidification and eutrophication than integrated farming due to the use of manure. However, the major drawbacks of the integrated system were the toxicity impacts related to heavy metals and phosphorous fertiliser. The second study on baby food is more recent (Sieti et al. 2019), which estimated the environmental impacts of ready-made porridge products for infants, considering 'cradle to grave' system boundary and identifying the environmental hotspots along the supply chain.

Therefore, this paper aims to fill this knowledge gap by quantifying for the first time the environmental impacts of a range of ready-made baby foods available in the UK. The UK was chosen due to its well-developed baby food market (Mintel 2013). However, similar or identical products are on sale in many developed countries and, therefore, the key findings of this work should be applicable elsewhere. Different product groups were also considered to estimate the extent to which food choices affect the environmental impacts and their trade-offs with nutritional value. In addition, the impacts associated with different types of diet were assessed and possible improvement opportunities suggested. It is expected that the results of this study will be of interest to baby food manufacturers and consumers as well as LCA practitioners.

2 Methods

The study was carried out following the ISO 14040/14044 methodology (ISO 2006a; ISO 2006b). The methodology, data and the assumptions are described in more detail in the following sections.

2.1 Goal and scope of the study

The goal of the study was to assess the environmental impacts of a number of ready-made baby foods, both in comparison to each other and as part of an overall weekly diet. The focus was on solid foods consumed by babies from the age of seven months onwards, when this type of food is typically introduced into their diet to complement milk.

The following 12 food products were chosen for assessment across the three daily meals:

1. breakfast: wet and dry porridge¹;
2. lunch: chicken; vegetable and chicken risotto; spaghetti Bolognese; vegetable lasagne; salmon risotto; and
3. dessert: apple, pear and banana; strawberry, raspberry and banana; strawberry yoghurt; apples and rice; banana and chocolate pudding.

The above products were selected based on the authors' market analysis, covering all food groups in the "Eat Well Plate" (Public Health England 2016). Based on the dietary guidelines in the latter, the following six ingredient groups were considered: i) meat, poultry and fish; ii) dairy (milk, yoghurt and cheese); iii) cereals; iv) vegetables and beans; v) fruits; and vi) oils and sugar. Instead of assessing the impacts of all ingredients, similar ingredients were grouped; for example, milk, cheese and yoghurt were grouped into dairy foods. The same approach is also commonly followed in diet assessments (Milà i Canals et al. 2011). Thus, the aim was to determine what food groups make the highest contribution to the environmental footprint of an omnivorous diet. The latter is the most common diet because diversity of food is considered healthy for babies. In the UK, a well-balanced diet, including all food groups, is advised as early as at the start of weaning (Venter and Harris, 2009) as studies have shown that early consumption of a well-balanced diet promotes healthy development in infancy and influences a healthy eating lifestyle in adulthood (Benelam et al. 2015). Although vegetarian diets are considered to be healthier, evidence of this in high-

¹ Wet porridge contains liquid milk and is sold ready to eat. Dry porridge contains milk powder and is sold in dry form, requiring the addition of hot water before consumption.

income countries for infants, children and adolescents is inconclusive (Schürmann et al. 2017).

Two functional units were considered:

1. Individual meals: “one ready-made meal consumed by a baby at home”, equivalent to a serving of 125 g.
2. Weekly diet: “three ready-made meals – breakfast, lunch and dessert – consumed by a baby at home each day over a week”, with each meal equivalent to a serving of 125 g. This functional unit is based on the findings of market research: 8% of UK babies consume ready-made baby food four times or more per day, 22% 2-3 times per day, 32% once per day, 19% 2-3 times per day and 19% once per week or less (Mintel 2013).

The product formulations are based on information obtained from major UK retailers to ensure that they are representative of the recipes across the sector, focusing on conventional and excluding the organic sub-sector. A total of 513 commercially produced baby food products were sampled, produced by five leading companies selling baby food in the UK.

The guiding principle for the choice of food groups and ready-made meals was the percentage frequency by which different food items appear on the front product label and in the recipe description. Based on this analysis, the most consumed foods are apples and bananas in the fruit group, carrots, tomatoes and potatoes in the vegetables group and chicken and beef in the meat group (see Table S1 in the Supplementary Information (SI)). This information was combined with the identification of best-selling products on the UK market, as reported by Amazon. As a result of this analysis, the above-mentioned 12 baby meals produced by all food brands found on the UK market were selected for the analysis. Their formulations can be found in Table S2 in the SI. It should be noted that the product formulations represent an average across the market and hence do not correspond exactly to the actual products found on supermarket shelves.

The system boundaries were from “cradle to grave”, as indicated in Figure 1. These encompass the production and processing of raw materials (ingredients), the manufacture of the ready-made baby food, the production of packaging materials, product distribution, retail, consumption and end-of-life (EoL) waste management. The consumption stage involves heating up the food using a gas hob. The construction of infrastructure is excluded as its impacts are typically low due to long lifetimes (Ecoinvent 2015). These stages are discussed in turn below.

2.2 Inventory data

As mentioned above, the data for the composition of the meals were collected through the authors’ market research while the manufacturing data were sourced from literature (Mattsson 1999a). Background life cycle inventory data were sourced from Ecoinvent V3.1 (Ecoinvent 2015) where available and supplemented by data from literature or own estimates, as summarised in Table S3 in the SI and detailed below. Where stated, the background data were adjusted for UK conditions with respect to the electricity mix and transport distances.

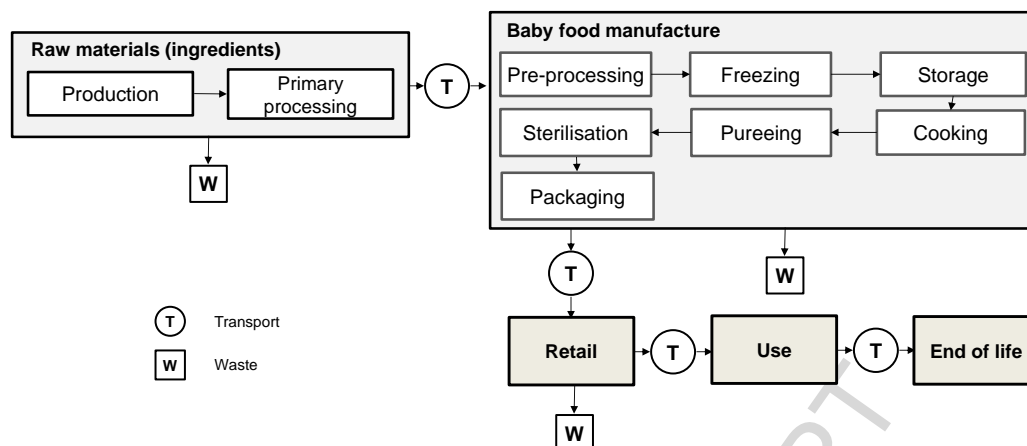


Figure 1 System boundary and the stages in the life cycle of the baby ready-made meals

Wherever possible, data sources were harmonised in terms of methodological consistency based on their system boundaries, allocation methods and coverage. Where that was not possible (e.g. in cases of inconsistent data), completeness checks were performed in relation to the goal and the scope of the study. Where multiple background data sources existed, particularly for raw materials, the impacts for each dataset were compared to ensure that the selected datasets fell within a typical range. Other data quality considerations included geographical and technological representativeness, to explore the effect of data uncertainty on the results. As products were assumed to be sold and consumed in the UK, UK specific data were used wherever possible. Data from elsewhere were adapted to UK conditions as mentioned above. The manufacturing data, although obtained from the literature (Mattsson 1999a; b) were judged to be technologically representative as they were provided by industry.

The allocation methods applied to the foreground systems modelled in this study were chosen such that, where a market is already established, economic allocation was used, whereas in other cases system expansion was applied. The details are discussed in the following sections.

Based on the above, the data can be considered sufficiently robust and prove the validity of the methodology. Any areas of particular uncertainty are highlighted in the next sections.

2.2.1 Raw materials (Ingredients)

For the ingredients, where available and known, country specific data were used, based on the statistics from DEFRA and other sources, as detailed below.

2.2.1.1 Meat- and fish-based ingredients

Chicken: The UK is the largest chicken meat producer in the EU with 77% self-sufficiency, mainly importing from Thailand (41% of imports) and Brazil (13%) (AHDB 2015a). In terms of tonnage, 53% of the imports are fresh/frozen poultry, 40% processed and 7% salted, with a similar trend in terms of value (AHDB 2015a). To represent the UK as closely as possible, it was assumed that 77% of chicken consumed is British and the rest is Brazilian frozen, packed poultry (as no inventory data were available for Thai chicken imports). For British chicken, data from Williams et al. (2006) and Foster et al. (2006) were used to model the system both for UK broiler raising and the broiler processing industry. For feed, maize grain was used instead of sunflower meal and soya oil instead of soya meal (Ecoinvent 2015) based on availability of inventory data. Wheat straw was also used as bedding, as the type of bedding varies based on animal welfare standards. A British chicken at intensive farming was assumed to be of 2.2 kg live weight. Plastic waste from packaging was assumed to be landfilled and wastewater treated in a treatment plant (Ecoinvent 2015). For Brazilian chicken, the LCA data were sourced from Prudêncio da Silva et al. (2014).

Beef: UK production covers almost 80% of total consumption, with beef deriving from both the suckler herd and the dairy herd, with almost equal shares (AHDB 2015b). The inventory for beef at farm was based on Williams et al. (2006) for an average of Upland suckler herds (autumn/spring calving) and Hill suckler herds, as 50% of cows contributing to prime carcass beef are suckler herds (EBLEX 2010). Data for slaughtering of cattle were taken from Nielsen et al. (2003) and adapted to UK electricity mix. Electricity consumption for freezing of cattle meat was also based on Nielsen et al. (2003).

Salmon: Atlantic salmon farmed in Scotland dominates UK aquaculture harvest and the UK is a leading aquaculture producer in the EU (Ellis et al. 2012). The main steps are fishmeal and oil production, trout feed production, salmon farming and salmon filleting. Although feed ingredients vary between countries, historically, the two most important ingredients in fish feed have been fish meal and fish oil (Marine Harvest 2016). Data from Nielsen et al. (2003) were used to model fishmeal and oil production.

Trout feed composition (materials) was modelled based on Nielsen et al. (2003) and utilities input for feed production was based on Winther et al. (2009), adjusted to UK electricity mix. The feed input for salmon production at farm was based on Pelletier et al. (2009), adapted for UK conditions. Data for salmon farming and processing (filleting and freezing) were adjusted to UK conditions from Winther et al. (2009). Ice production was based on Nielsen et al. (2003).

2.2.1.2 Dairy-based ingredients

Milk production: According to Rabobank (2016), the UK is largely self-sufficient in liquid milk production and hence UK-based data were used. The life cycle environmental impacts of milk from cradle to farm gate were modelled based on Williams et al. (2006) for animal feed, whereas for manure output, data were based on Weiss & St-pierre (2010). For water requirements, data from DairyCo (2013) were used, in addition to energy inputs at the farm from Upton et al. (2013). Data for activities beyond the farm gate were taken from Eide (2002) and adapted to UK conditions. For milk powder, data were based on Nielsen et al. (2003). For environmental impacts of milk, see Sieti et al. (2019).

Cheese: Yellow semi-hard cheese was considered in the study and its production was modelled based on Nielsen et al. (2003), using the milk production data as above and adapting the electricity mix to UK conditions.

Yoghurt production: Yoghurt production was modelled based on data in Ecoinvent (2015), excluding data for flavoured yoghurts and adapted to UK conditions. Like cheese production, the milk data were the same as described above.

2.2.1.3 Cereal-based ingredients

Oats: Oats are used for porridge but life cycle inventory data were not available. Instead, barley seeds were used as a proxy for oat seeds (Ecoinvent 2015). This is a reasonable assumption as both crops involve similar agricultural activities, grow under similar climatic conditions and have comparable yields. Information for field operations was taken from Van Zeist et al. (2012), McDevitt & Milà i Canals (2011) and Nemecek & Kagi (2007). Production of fertilisers and fertiliser impacts were based on IPCC (2006). For oat flakes production, data from Nielsen et al. (2003) were used and waste was assumed to be composted, in accordance with the waste management practice in the food and drink industry (Bartlett 2010; Carr & Downing 2014).

Rice and corn flour: US rice, at farm, was considered, based on data from Ecoinvent, while data for wheat flour production were used as a proxy for the subsequent flour production (Nielsen et al. 2003).

US corn was considered for corn flour because the US is a global leader in maize production (International Grains Council 2016). Data from Ecoinvent were used for corn cultivation. For flour production, data for rye milling from Nielsen et al. (2003) were used as a proxy. Composting was considered for treatment of bio-waste (Ecoinvent 2015).

Pasta: As the European market is dominated by Italy, dry pasta production in this study was based on Lo Giudice et al. (2011), representing Italian pasta made from durum wheat/semolina. Wheat production for global production was sourced from Ecoinvent (2015).

2.2.1.4 Vegetables, beans and fruit-based ingredients

Tomatoes: Classic loose tomatoes were considered, as these account for the majority of tomatoes cultivated in the UK (Caspell et al. 2006), the Netherlands and Spain. Data for tomatoes consumed in the UK were based on imports to the UK by country (Defra 2016): 20% UK produced, 27% Dutch, 32% Spanish and 21% others (global production). Different systems can be distinguished in the aforementioned countries: Spanish tomatoes are cultivated in open field on soil, while the UK and the Netherlands grow tomatoes in heated greenhouses. Therefore, the corresponding consumption of energy, water, fertilisers, and pesticides were considered, together with transport and yield. Field tomatoes from Spain were modelled based on Theurl et al. (2014) and Dutch tomatoes based on Antón et al. (2012). For the UK tomatoes, yield, water and energy input were based on Williams et al. (2006), while the amount of pesticides and fertilisers were based on similar production conditions in the Netherlands (Antón et al. 2012). Production of pesticides for the UK conditions was based on McDevitt & Canals (2011). To account for the emissions associated with heat, electricity and CO₂ enrichment, the ratio of gas and electricity used in greenhouses was calculated based on data published by the Horticultural Development Council (2002). Life cycle inventory data representing global production were sourced from Ecoinvent.

Potatoes: The UK's potato demand exceeds domestic supply, with main imports from the Netherlands and Belgium (AHDB Potatoes 2016). The only data found in Ecoinvent for Europe were from Switzerland, with a yield of 37.8 t/ha. This is close to the UK equivalent of 44.7 t/ha (AHDB Potatoes 2016). Hence, data for Swiss potatoes were used.

Carrots: Data on the production of carrots were taken from Ecoinvent, representing global average production conditions for open field cultivation.

Peas: Peas are produced widely in the UK, although the UK is a net pea importer (The Andersons Centre 2015); however, no UK-based LCA data were available for peas. Based on 2015 data by value, Spain was the highest exporter of peas to the UK (International Trade Centre 2015). Therefore, peas from Spain were considered based on data in Ecoinvent.

Swede and parsnip: Data from Sweden (Davis et al. 2011) were used due to a lack of UK data. Only global warming potential (carbon dioxide and nitrous oxide) was considered as data for other impacts were not available.

Courgettes and onions: Data from Ecoinvent, representing global average conditions, were used; country-specific data were not available.

Bananas, apples and pears: As bananas are not produced in the UK, global production data for bananas were used from Ecoinvent. Apples and pears are produced in the UK but due to a lack of data, global production (that includes UK production) was considered instead.

Berries: The UK produces both raspberries and strawberries but also imports both fresh and frozen produce from all over the world. However, a lack of inventory data for production of

raspberries meant that an average global dataset for strawberries from Ecoinvent had to be used to represent both types of berries.

Cocoa powder: The UK is the seventh largest cocoa grinder in the EU, with almost all of cocoa beans imported from Ivory Coast (57%) and Ghana (42%) (CBI - Ministry of Foreign Affairs 2016). Due to a lack of data for Ivory Coast, only the data for cocoa production and processing in Ghana were used, including mass allocation between the by-products (Ntiamoah & Afrane 2008). Land use change was excluded due to high uncertainty in the data (Jeswani et al. 2015). NPK fertilisers were assumed to contain 15% wt of N, 15% of P₂O₅ and 15% of K₂O. LCA data were sourced from Thinkstep (2015) as Ecoinvent data were not available for this specific composition.

2.2.1.5 Oils and sugar

Sunflower oil: For sunflower oil, global production data were used from Ecoinvent, since no data for UK imports were found. Global production of sunflower seed oil is dominated by Russia, Ukraine, Argentina and Europe (FAO 2010). For sunflower oil production, process data for rapeseed crushing were used as a proxy (Nielsen et al. 2003).

Rapeseed oil: The UK is the third largest rapeseed producer in the EU and is self-sufficient, with the main driver being the biodiesel industry (Krautgartner et al. 2016). For rapeseed production, data were sourced from Ecoinvent, while the crushing and oil production process was based on Nielsen et al. (2003).

Palm oil: Malaysia is one of the main sources of palm oil in the UK (Defra 2012). Hence, Ecoinvent data for its production in Malaysia were selected for consideration.

Sugar: Most sugar is imported to the EU from Brazil (International Sugar Organization 2014) and hence sugar cane was considered in the study, using data from Ecoinvent.

2.2.2 Manufacturing

The resources used in the manufacturing process are summarised in Table S4 in the SI. Typically, heat is used for cooking and sterilisation and electricity for milling, mixing, homogenisation, packaging and lighting (O'Shaughnessy 2013). Manufacturing data for both lunch and dessert meals were based on data in Mattsson (1999a). According to that study, 1.5 MJ of electricity, 11.16 MJ of natural gas and 0.014 MJ of diesel are required for the production of 1 kg of carrot puree. These data encompass pre-processing, freezing, storage, cooking, pureeing and sterilisation, and were provided by a major Swedish baby food producer. Since all but two products (dry porridge and yoghurt) considered here are pureed and therefore involve the same processing steps, the above energy demands were assumed for all the products. The amounts of chemicals and water used were also sourced from Mattsson (1999a), while the type of chemicals was from Eide et al. (2003). For dry porridge, the manufacturing data were sourced from Sieti et al. (2019). It was assumed that all wastewater is treated in a wastewater treatment plant (Ecoinvent 2015). Food waste was assumed at 7% of the product, which is within the range for different commodity groups (Bond et al. 2013; Jeswani et al. 2015). Food waste was assumed to be composted, following the current waste management practice in the food and drink industry (Bartlett 2010; Carr & Downing 2014).

2.2.3 Packaging

As ready-made baby foods are typically packaged in jars, this type of packaging was considered, comprising a glass jar and an aluminium lid. White glass data from Ecoinvent were used, whereas the lid data were based on Amienyo (2012), composed of 84% aluminium and 16% plastics. Data for these materials were taken from Ecoinvent. The only exception to this is dry porridge, which is packaged in a plastic bag and a cardboard box (Sieti et al. 2019). For further details on the packaging, see Table S5 in the SI.

2.2.4 Retail

The ready-made meals are distributed from the manufacturer to the retailer where, based on its best-before date, they have an average shelf-life of 12 months. However, being fast-moving consumer goods (FMCG), in reality they stay at the retailer for a shorter time. Therefore, retailing of FMCG stored at room temperature was assumed, using data from Nielsen et al. (2003). Pasta was assumed a representative FMCG, in the absence of data for baby food. The data take into account the average flow of products and the area occupied, including energy consumption, heat and electricity (lighting) for a large retail store with an area of 1350 m². The selection of the retailer size was based on the fact that ready-made baby foods are sold mainly in hypermarkets and supermarkets. Based on Nielsen et al. (2003), the amount of electricity used per functional unit for the lighting of the aisle and checkout area was taken to be 468 kJ; 273 kJ was assumed for heating. Food losses at the retailer were considered to be 2% of the product sold (Canals et al. 2007).

2.2.5 Use

The use stage includes heating up the meal on a hob (or water in the case of dry porridge), manual washing of the dishes and waste disposal. While the meals can also be heated up in a microwave, hobs tend to be used more often in households with children to avoid overheating of food (Hulme et al. 2011). The majority of hobs in the UK (61%) are gas-fired (Defra 2013). Therefore, a gas hob was considered, with an average energy consumption of 0.063 kWh per meal, except for dry porridge where water heating requires 0.05 kWh. Both values were determined using a smart meter. For washing up the plates and cutlery, the use of 1 L of tap water was assumed (Defra 2008). The resulting wastewater is treated in a municipal wastewater treatment plant, with inventory data sourced from Ecoinvent. Post-consumer food waste was also considered, assuming 14% of food being wasted (Holding et al. 2010).

2.2.6 Waste management

The waste management options are summarised in Table S6 in the SI, together with the amounts of waste generated in different life cycle stages. As discussed above, material losses of 7% were considered in the food manufacturing, 2% in the retail stage and 14% at the consumer. Food waste from manufacturing is composted and the resulting fertiliser land-spread (Bartlett 2010; Carr & Downing 2014). Waste generated at the retailer was assumed to be landfilled due to difficulties in separating out the packaging. The only exception is the cardboard box used for dry porridge. The treatment of household food waste followed the UK waste management practice (Defra 2015a), with 12% of the food waste recycled as compost, 55% incinerated and the rest landfilled. Post-consumer packaging was also assumed to be treated based on the UK practice (Defra 2015b), as detailed in Table S6.

2.2.7 Transport

Table S7 in the SI provides an overview of the transportation modes and distances assumed in the study. All road transport data were sourced from Ecoinvent, assuming the use of a diesel lorry (Euro 3) and a distance of 100 km. The use of transoceanic freight was considered for the transportation of imported ingredients and Google maps were used to calculate the transoceanic distances. For consumer shopping, a round-trip of 7.9 km was assumed, based on the average food shopping distance per week per household and an average domestic food basket of 10 kg per week per person (Pretty et al. 2005). Diesel was considered to be the main fuel for vehicles, except for petrol car used for shopping. The transportation from home to waste disposal was not considered.

2.2.8 Allocation and system expansion

Multiple materials in the life cycle under study have associated by-products, necessitating allocation. These are detailed in Table S8 in the SI.

2.2.9 Weekly diet scenarios

Different menu scenarios were developed for the ready-made meals, based on the following four types of diet: omnivorous (baseline), vegetarian, pescatarian and dairy-free. The four diets were derived by rotating the sample of the 12 ready-made meal options, excluding those that are prohibited in the non-omnivorous diets.

The Infant Feeding Survey (IFS) showed that three solid meals a day were given to babies incrementally during their first year, in addition to milk feeds (McAndrew et al. 2012). However, there are no formal recommendations for portion sizes. According to a sample weekly menu for babies seven to nine months of age by The Caroline Walker Trust (2011), the total solid food consumption is around 375 g per day for home-made meals. Three servings of ready-made baby foods were assumed here: breakfast, lunch and dessert. Based on the functional unit (125 per meal), the food intake in one day is therefore 375 g. This is congruent with the abovementioned intake of solid food of 375 g. Drinks are excluded and it was assumed that both boys and girls consume the same amount of food. The contribution of different food groups to the weekly menu considered here is outlined in Table 1 for each diet; the list of meals included in the menu for each diet can be found in Table S9 in the SI.

Table 1 Four diet scenarios considered in the study

Type of diet	Meat, poultry & fish	Dairy	Cereals	Vegetables, beans & fruits	Oils & sugar
Omnivore	4%	20%	32%	23%	21%
Vegetarian	0%	23%	30%	23%	25%
Pescatarian	4%	22%	38%	18%	19%
Dairy free	7%	0%	24%	64%	4%

2.2.10 Impact assessment

The LCA modelling was carried out using Gabi LCA software V6.1 (Thinkstep 2015). The impacts were estimated according to the CML 2001 method (Guinée et al. 2002), updated in 2015. This method was selected as it is used widely in LCA studies but also to enable the inclusion of the impacts of porridge, estimated previously using the same method (Sieti et al. 2019). To ensure completeness and to avoid imposing value judgements in the selection of impacts, all 11 default CML 2001 categories were considered. These are as follows: global warming potential (GWP), abiotic depletion potential of elements (ADPe), abiotic depletion potential of fossil resources (ADPf), acidification potential (AP), eutrophication potential (EP), freshwater ecotoxicity potential (FAETP), human toxicity potential (HTP), marine ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical oxidant creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

It should be noted that other impacts may also be of relevance to the food sector, such as land occupation, transformation and competition as well as the water footprint. However, these could not be estimated due to a lack of data and could be considered in future studies.

3 Results and discussion

The results of the assessment are discussed first for individual meals, then by food group and finally in terms of weekly diet.

3.1 Environmental impacts of individual meals

The environmental impacts of the 12 ready-made meals are detailed in Figure 2a-k for each of the 11 categories considered. Overall, the lunch meals were found to have higher impacts than the breakfast and dessert options. Among the lunch meals, the products with the highest impacts are spaghetti Bolognese and salmon risotto. For desserts, strawberry, raspberry and banana as well as apple, pear and banana purees have the lowest impacts. Dry porridge has the lowest impacts overall across all the categories, except for

eutrophication and terrestrial ecotoxicity. Wet porridge has higher impacts than the dry, but lower than most other meals, except in the case of acidification, photochemical oxidants formation and terrestrial ecotoxicity. Further details are provided in the following section, comparing the meals for each impact category in turn. When a common trend was identified, impact categories and the life cycle hotspots were grouped. All the impacts discussed below are expressed per functional unit of 125 g serving and hence this is omitted from the units for brevity. Note that the impacts of porridge were estimated previously by the authors (Sieti et al. 2019) but are included here for completeness.

3.1.1 Global warming potential (GWP)

The lunch meals with the highest GWP are spaghetti Bolognese with 689 g CO₂ eq. and salmon risotto with 503 g CO₂ eq. (Figure 2a). The lowest impact among the lunch options is found for the chicken-based meal at 401 g CO₂ eq. Among the dessert options, the banana and chocolate pudding have the highest GWP (432 g CO₂ eq.), while the strawberry, raspberry and banana meal has the lowest value (312 g CO₂ eq.), followed closely by apple, pear and banana (316 g CO₂ eq.). The impacts of the breakfast options are estimated at 141 and 363 g CO₂ eq. for dry and wet porridge, respectively.

Thus, as expected, the GHG emissions are much higher for the animal-based than for the plant-based products. Raw materials are particularly dominant for spaghetti Bolognese due to the high emissions associated with beef production and tomato cultivation in greenhouses.

3.1.2 Abiotic depletion potential of fossil resources (ADPf)

As shown in Figure 2c, the meal with the highest ADPf is spaghetti Bolognese with 7.3 MJ, followed by vegetable lasagne at 5.55 MJ. The other meals have a relatively similar impact, ranging from 3.85 MJ for wet porridge to 4.96 for the two risotto options. Dry porridge is an exception with a much lower impact of 0.79 MJ. The best lunch and dessert alternatives are the chicken meal (4.49 MJ) and strawberry yoghurt (3.96 MJ), respectively. All the meals benefit from the credits for packaging recycling and waste food composting, reducing the total impact by 7%-13%, depending on the meal type (Figure 2c).

3.1.3 Eutrophication potential (EP)

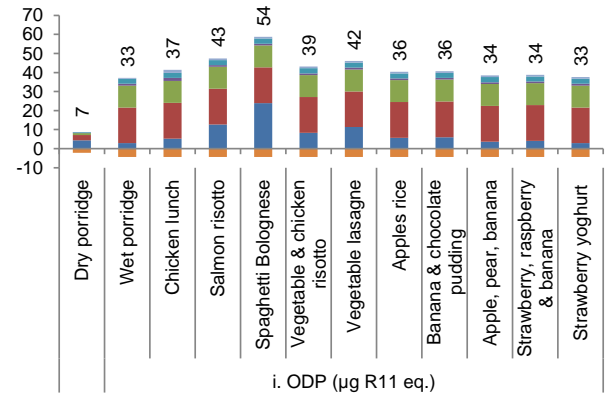
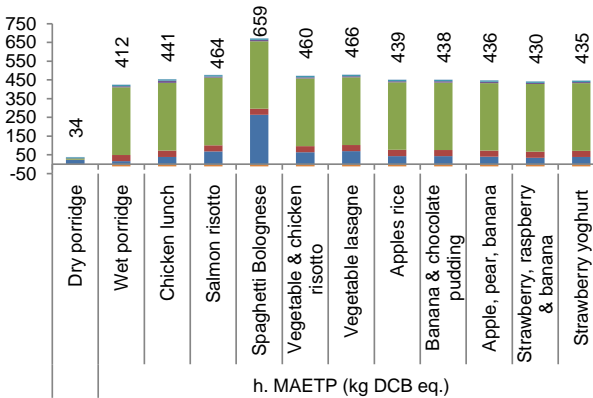
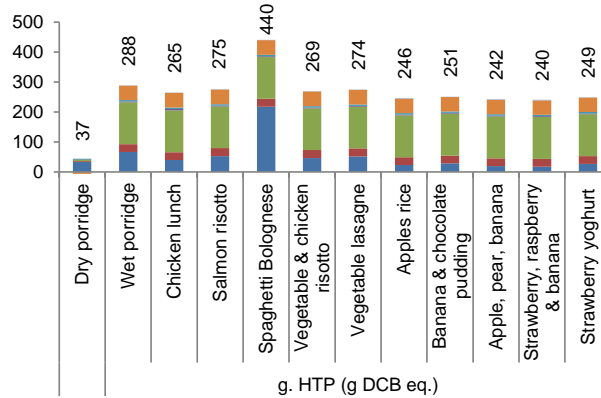
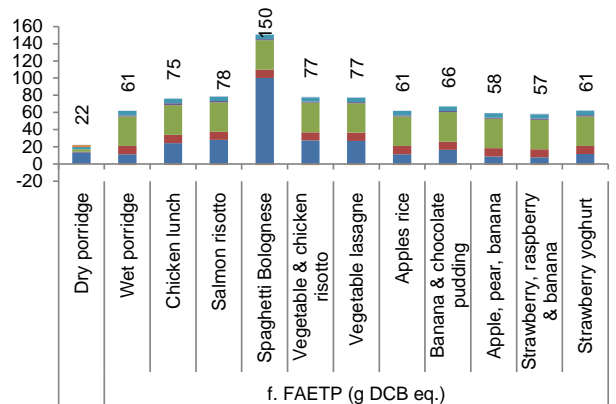
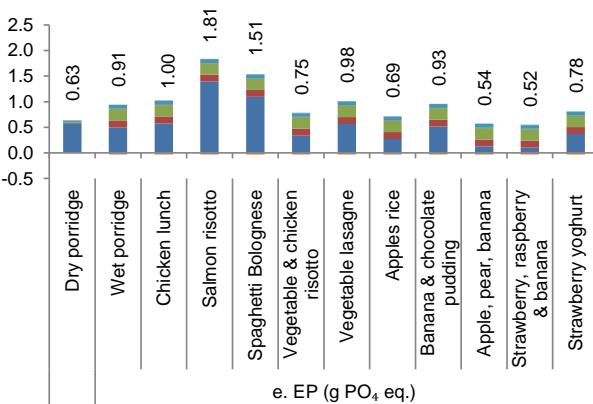
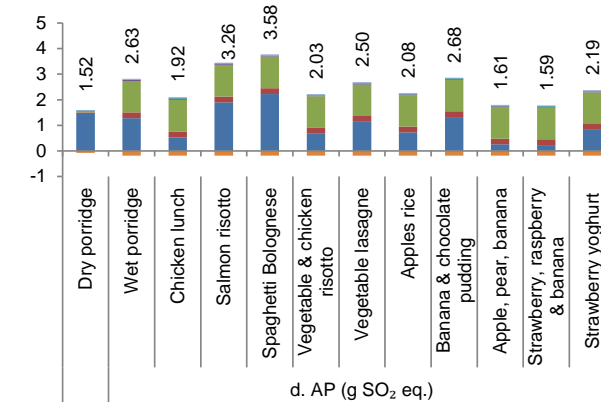
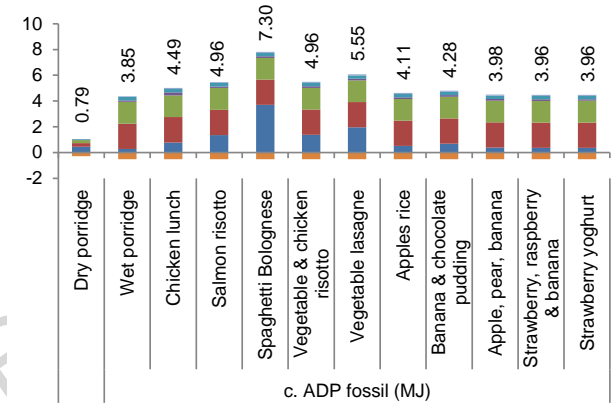
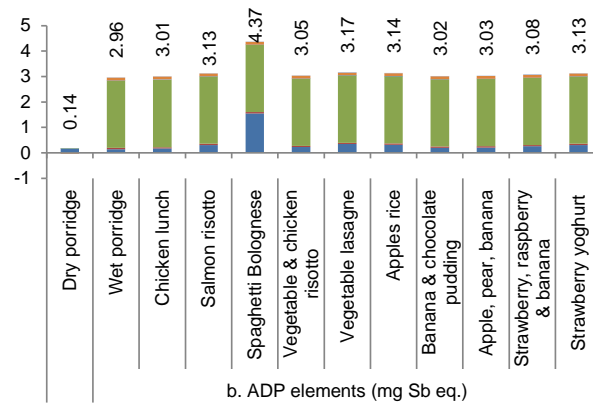
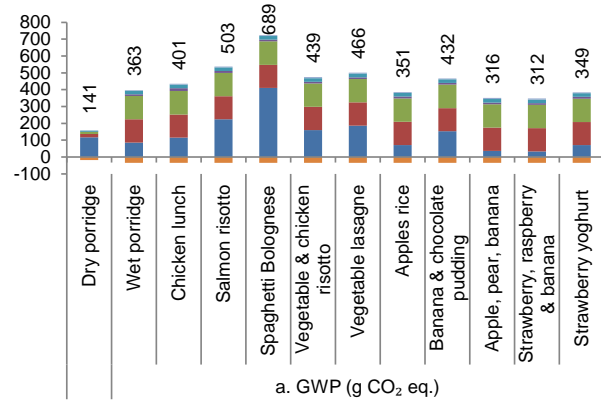
Overall, the EP varies between 0.52 g PO₄ eq. (strawberry, raspberry and banana dessert) and 1.81 g PO₄ eq. (salmon risotto). The lunch option with the lowest impact is vegetable and chicken risotto at 0.75 g PO₄ eq. (Figure 2e). The breakfast meals have an estimated impact of 0.63 (dry) and 0.91 g PO₄ eq. (wet). The latter is comparable to the worst dessert option, banana and chocolate pudding (0.93 g PO₄ eq.).

3.1.4 Photochemical oxidants creation potential (POCP)

Contrary to the trend found for the other categories, the meal with the highest impact is wet porridge with 299 mg C₂H₄ eq. (Figure 2j). This is mostly due to the emissions from sugar refining. Spaghetti Bolognese and salmon risotto are the next worst options (282 and 220 mg C₂H₄ eq., respectively). The impact from the remaining products is relatively similar, ranging from 136 to 186 mg C₂H₄ eq. Dry porridge has again the lowest impact (92 mg).

3.1.5 Terrestrial ecotoxicity potential (TETP)

Spaghetti Bolognese has by far the highest impact of 16.8 g dichlorobenzene (DCB) eq. (Figure 2k). This is 2.5 times greater than the next worst option, vegetable lasagne (6.8 g DCB eq.). The best lunch meal for this category is vegetable and chicken risotto with 0.7 g DCB eq. The desserts typically have the lowest impact, ranging from -1 g DCB eq. for the banana and chocolate pudding to 2.3 g BCD eq. for the strawberry yoghurt. The TETP is net negative for the former due to a relatively high amount of rice and the related uptake of heavy metals from the soil (Ecoinvent 2015).



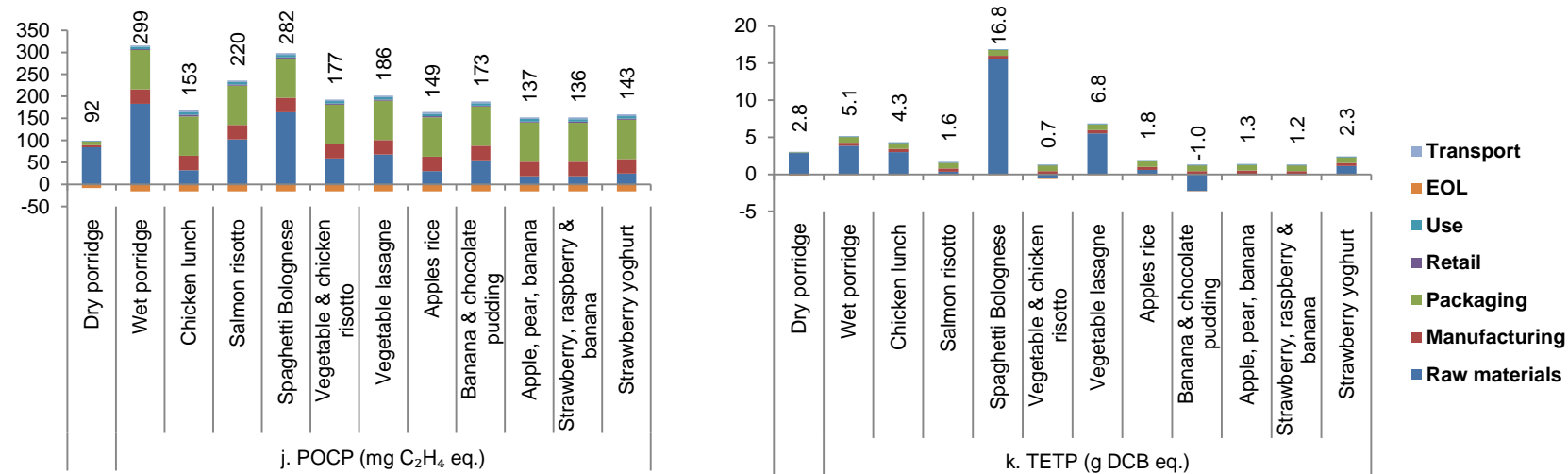


Figure 2 Environmental impacts of ready-made meals considered in the study

[a. Global warming potential (GWP), b. Abiotic depletion potential of elements (ADPe), c. Abiotic depletion potential of fossil resources (ADP_f), 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 oxidants creation potential (POCP), k. Terrestrial ecotoxicity potential (TETP). DCB: dichlorobenzene.]

3.1.6 Other impact categories

For the rest of the impact categories, spaghetti Bolognese has consistently the highest impact (Figure 2). The second worst option tends to be salmon risotto or vegetable lasagne. Consequently, the lunch options typically have higher impacts than the breakfast porridge or desserts, and dry porridge in particular has the lowest impacts.

3.1.7 Contribution analysis

As can be seen in Figure 2, the life cycle stages with the highest contribution across all impact categories are the raw materials, manufacturing and packaging. The raw materials play a considerable role for GWP (11%-84%), eutrophication (20%-91%) and terrestrial ecotoxicity (1%-221%). They are also the main contributor (4%-90%) to the other toxicity-related impact categories. These impacts are strongly influenced by fertiliser requirements associated with crops, animal feed and manure. GWP is also affected by methane emissions associated with meat and dairy production. Raw materials are also a major contributor to photochemical oxidants creation (13%-92%) and acidification (15%-97%) due to emissions of sulphur dioxide and nitrogen oxides from the life cycle of electricity.

The manufacturing stage contributes significantly to depletion of fossil resources (27%-51%), GWP (14%-44%) and ozone depletion (35%-57%). This is related to the use of energy, and mostly due to natural gas.

The packaging stage dominates depletion of elements (12%-89%), acidification (3%-77%) and photochemical oxidants (9%-65%). It is also the second main contributor (after the raw materials) to most toxicity-related impact categories, causing 14%-58% of human toxicity, 20%-88% of marine and 13%-60% of freshwater ecotoxicity. The majority of these impacts are due to the production of glass and aluminium used for jars and lids, respectively.

The highest contribution of the use stage was found for depletion of fossil fuels and the ozone layer, GWP and freshwater ecotoxicity (3%-10%), related to the use of natural gas for heating up the meals. End-of-life waste management is a significant contributor to human toxicity (up to 20%) due to the emissions of particles from treatment of aluminium scrap. The influence of retail and transport is small, contributing up to 4% (ozone depletion).

Therefore, based on these results, the life cycle stages that should be targeted for improvements are the ingredients, the manufacturing process and packaging. For the ingredients, both agriculture and product formulation play a significant role and should be considered for reducing the impacts. Improvement options in agriculture include better manure management, use of alternative animal feeds and optimised application of fertilisers. Product formulation should target meat and dairy-based products, considering alternatives or reducing their quantities, while ensuring that the nutritional value of meals is not affected. Various manufacturing improvements could also be considered, including energy integration and optimisation and use of renewable energy sources. Finally, glass could be replaced by alternative packaging, such as plastic, aluminium or water-proof paper. However, their recyclability should also be taken into account to ensure that the impacts are not reduced at the expense of waste generation.

3.2 Environmental impacts of different food groups

Table 2 gives an overview of the average contribution of different ingredient groups to the environmental impacts of the meal options considered in the study. A more detailed contribution analysis can be found in Figure S1 in the SI.

As can be seen from Table 2, the greatest contribution is from meat-based ingredients, which cause almost 30% of the impacts. This is followed by more than 20% contribution from the dairy products, 15% each from the vegetables and beans and 10% each from the oils and sugar, cereals and the fruits.

This is in stark contrast to their respective contributions to the products' formulation on a mass basis, also summarised in Table 2. For example, the meat ingredients constitute on average 3% of the relevant meals so their contribution to the impacts is around eight times higher than their share in the meal recipes. A difference of almost three times is noticed for the fruits, except that here the trend is reversed: their contribution to the impacts is lower than their contribution to the meals' composition. For oils and sugar, the contribution to the impacts is almost two and a half times higher than their contribution to the recipes. The contribution to the impacts of vegetables and cereals is fairly similar to their mass share in the meals. Finally, for the dairy-based ingredients, the contribution to the impacts and the recipes is almost 1.5 times higher (Table 2).

Table 2 Average contribution of different food groups to meal recipes (mass and energy content) and to environmental impacts

Food group	Mass contribution to recipes (% wt.) ^a	Calorific contribution to recipes (% kcal)	Contribution to impacts (%)
Meat	3	5	27
Dairy	16	16	23
Cereals	15	36	15
Vegetables and beans	20	9	15
Fruits	31	19	10
Oils and sugar	4	15	10

^a The remaining balance is water (11%).

However, the specific contributions of different groups vary widely across the impacts, as indicated in Figure S1 in the SI. These can be summarised as follows:

Depletion of elements: The meat-based ingredients contribute 32% to the total impact, mainly due to cadmium, copper and lead depletion associated with beef production. This is attributable to the operation of cattle housing and the production of cattle feed, the latter of which is in turn linked to fertiliser production. Cereals and dairy follow with a contribution of >15% each due to similar reasons: the use of fertilisers and pesticides in cereals cultivation and the use of the latter as animal feed, both connected to dairy production.

Depletion of fossil resources: Here, the vegetable ingredients contribute the most (37%). This is largely due to natural gas consumption, particularly for the cultivation of greenhouse tomatoes. Cereals, meat and fruits are the next largest contributors (>15% each), associated with energy consumption during rice and apple cultivation as well as cattle rearing.

Acidification and eutrophication: The dairy group contributes 59% and 33% to these two impacts, respectively. This is related to ammonia and nitrate emissions from manure and livestock housing. Of the remaining food groups, only meat contributes more than 15% to acidification due to ammonia and nitrous oxide emissions from grassland, livestock production and fertiliser production and application. For eutrophication, both meat (31%) and cereals (15%) are significant for similar reasons.

Freshwater ecotoxicity: More than a third (32%) of this impact comes from the dairy-based ingredients. This is due to heavy metals emitted in the life cycle of coal electricity, used for the operation of cattle housing, as well as due to the insecticides used in the production of feed. For the same reason, meat causes 27% of the impact, followed by cereals (18%). The remaining food groups contribute <15% each.

Global warming: The dairy products cause most of the GWP (27%) because of GHG emissions by cattle and energy consumption for their production. This is followed by meat, cereals and vegetables and beans, which contribute around 20% each. This is primarily

associated with energy consumption and methane emissions during cattle rearing and rice cultivation as well as the energy used in greenhouses for cultivation of tomatoes.

Human toxicity: The meat-based ingredients are again the main contributor (37%), mostly because of chromium, arsenic and selenium emissions associated with fertiliser production. The next largest contributors are cereals with 17% (mainly due to dry pasta and rice) and vegetables and beans with 15% (driven by tomatoes, carrots and peas). This is related to pesticides and fossil fuels used in agriculture. Dairy products and fruits (mainly apples) add 11% each to the total impact for similar reasons.

Marine ecotoxicity: The meat group dominates again (32%) due to hydrogen fluoride and beryllium emissions from energy generation. Vegetables and beans add a further 20% and cereals 16% as a result of energy consumption and fertilisers used mainly for the cultivation of tomatoes, carrots and rice.

Ozone depletion: The cereals and vegetable groups cause 23% each, of the total impact, mainly associated with use of halons in the gas supply chain, particularly for rice flour and dry pasta production, but also from tomato cultivation in greenhouses. Meat and dairy groups are responsible for 21% and 12% of ozone depletion due to energy consumption for cattle rearing and cereals used as animal feed. Fruits add another 15% mainly due to energy consumption and fertilisers used for the cultivation of apples.

Photochemical oxidants and terrestrial ecotoxicity: Most of these impacts are related to sugar and oils (48% and 20%, respectively) due to oil or petroleum derivatives used as an energy source and carbon monoxide emissions from sugar manufacturing. Furthermore, meat causes 21% of photochemical oxidants, associated with the life cycle of energy used in its production. It also contributes 41% of the terrestrial ecotoxicity due to nitrate emissions from manure, as well as pesticides and fertilisers used in the production of animal feed. Dairy-based ingredients also contribute significantly to these two impacts (16% and 20%, respectively), influenced by the manure and fertilisers used for animal feed.

3.3 Environmental impacts of different diets

The impacts for the four weekly diets considered here are displayed in Figure 3, based on three meals per day (the 2nd functional unit in section 2.1). The contribution to the impacts of different food groups in these diets can be seen in Figure 4. As indicated in Figure 3, the variation in impacts is not significant between the diets. However, the dairy-free diet has notably higher human toxicity and marine ecotoxicity than the other three. These results are discussed below in more detail, taking the omnivore diet as the baseline. As mentioned earlier, this is the most common diet because diversity of food is considered healthy for babies.

Looking at the vegetarian diet first (Figure 3), the elimination of meat, poultry and fish from the diet leads to a slight decrease in most impact categories, with the greatest decrease found for eutrophication and freshwater ecotoxicity (6%). This is due to reduced phosphate and nitrate emissions from livestock rearing. However, there is a slight increase in depletion of fossil resources (2%) and terrestrial ecotoxicity (8%) due to the increase in dairy products as well as in oils and sugar to compensate the loss of meat-related ingredients.

For the pescatarian diet, when fish is the only meat-based ingredient on the menu, there is a significant reduction in terrestrial ecotoxicity (39%) compared to the omnivorous diet. This is primarily due to the reduced use of fertilisers and pesticides for cultivation of animal feed as beef and chicken are removed from the menu. On the other hand, eutrophication increases by 26% and acidification by 11% due to the high contribution of salmon in the meal recipes.

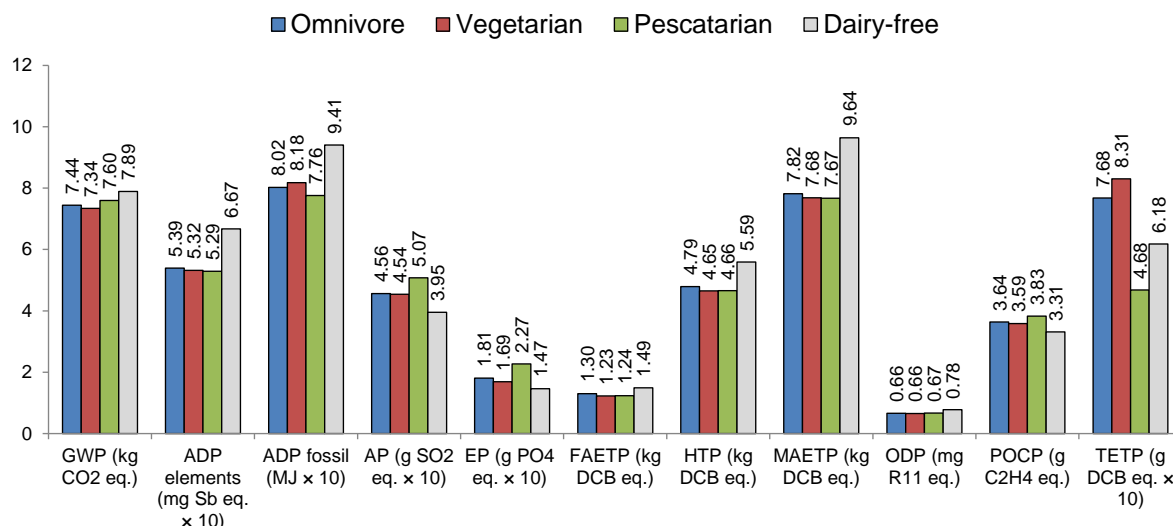


Figure 3 Environmental impacts of different diets [Impacts expressed per baby per week. For the acronyms, see Figure 2].

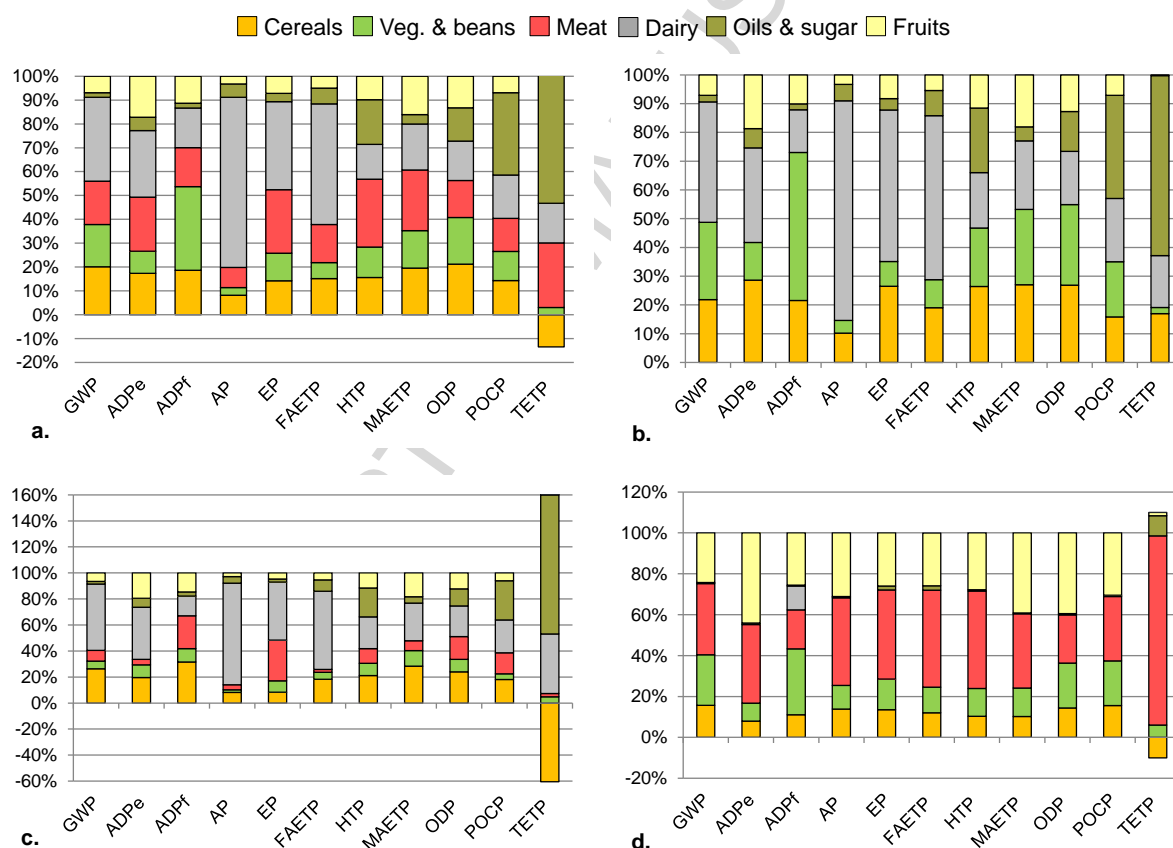


Figure 4 Contribution of different food groups to the environmental impacts of the four diets considered in the study [a. Omnivore, b. Vegetarian, c. Pescatarian, d. Dairy free. Contribution of water is excluded. For the acronyms, see Figure 2].

Finally, when the dairy-free diet is considered, all impacts are higher by 6%-24% relative to the omnivore diet. When dairy is eliminated, there is an increase in the meat-based ingredients of 3% compared to the baseline as the non-dairy meals are rotated in the menu to make up for the lack of dairy products. This leads to a ‘spill over’ of meat-related impacts into the dairy-free diet from the lunch products. Spaghetti Bolognese is the main lunch meal

to substitute others as it uses no dairy ingredients, but it has high impacts as discussed in section 3.1. Interestingly, acidification, eutrophication, photochemical oxidants and terrestrial ecotoxicity reduce by 9%-19%, mostly related to the absence of dairy products as well as the reduction in the oils and sugar.

In comparison with each other, the vegetarian and pescatarian diets have similar impacts, which are lower than for the dairy-free diet for most categories, except for acidification, eutrophication, photochemical oxidants and terrestrial ecotoxicity.

Overall, eutrophication increases with the contribution of fish-based meals in the menu. Furthermore, depletion of elements is higher in the dairy-free diet but eutrophication, acidification and terrestrial ecotoxicity are lower.

These dietary impacts can be contextualised with reference to the annual GWP of an adult omnivore diet, which is estimated at 1.89 t CO₂ eq. per person (WWF 2017). The annual impact of the baby omnivore diet determined in this study is 387 kg CO₂ eq. per baby, based on the weekly GWP of 7.44 kg CO₂ eq. (Figure 3). This is around five times lower than the impact of an adult. However, there is also a five times difference in the calorie intake, with adults consuming around 2000 kcal per day and babies around 400 kcal from solid foods (The Caroline Walker Trust 2011), equivalent to 375 g of food eaten daily considered here. Therefore, the results compare well, confirming the validity of the estimates. The weekly menu for different diets considering the average calorie content in baby food is discussed further in the next section.

3.4 Considering the nutritional value of meals

The nutritional value of the individual meals is summarised in Figure 5, estimated based on data from FatSecret (2019) on the calorie content of ingredients and their mass contribution to the recipes. The average calorific contribution of different food groups to the meals can be found in Table 2.

As can be seen from Table 2, the majority of energy comes, on average, from cereals (36%) which cause 15% of the impacts; the latter contribution is incidentally identical to their mass share in the meals. The respective contributions of fruits and vegetables to the impacts are 10% and 15%, compared to their energetic contributions of 19% and 9%. This is despite them having the highest mass shares in the meals of 31% and 20%, respectively. On the other hand, meat contributes only 5% of the energy content but 27% of the impacts – a factor of five difference.

The contribution of dairy-based ingredients to the impacts is approximately 1.5 times greater than their contribution to the calorie content: dairy products account for 16% of the energy in meals, incidentally identical to their mass contribution, but contribute on average 23% to the impacts. Finally, the contribution to the impacts of oils and sugar is almost 2.5 times higher than their mass share in the recipes but 1.5 lower than their contribution to the energy content (Table 2); this can be explained by the high caloric value of oils and sugar.

Considering weekly menus, as mentioned previously, babies consume around 400 kcal from solid foods per day (The Caroline Walker Trust 2011), or 2800 kcal per week. In the “Eat Well Plate” (Public Health England 2016) the suggested weekly calorie targets per food group are that 12% should come from meat (336 kcal), 15% from dairy (420 kcal), 33% from cereals (924 kcal), 33% from vegetables and fruits (924 kcal) and 7% from oils and sugar (196 kcal). It should be noted, however, that these nutritional targets represent average estimates and act as indications rather than rules to follow as diet is subject to each baby’s specific developmental needs.

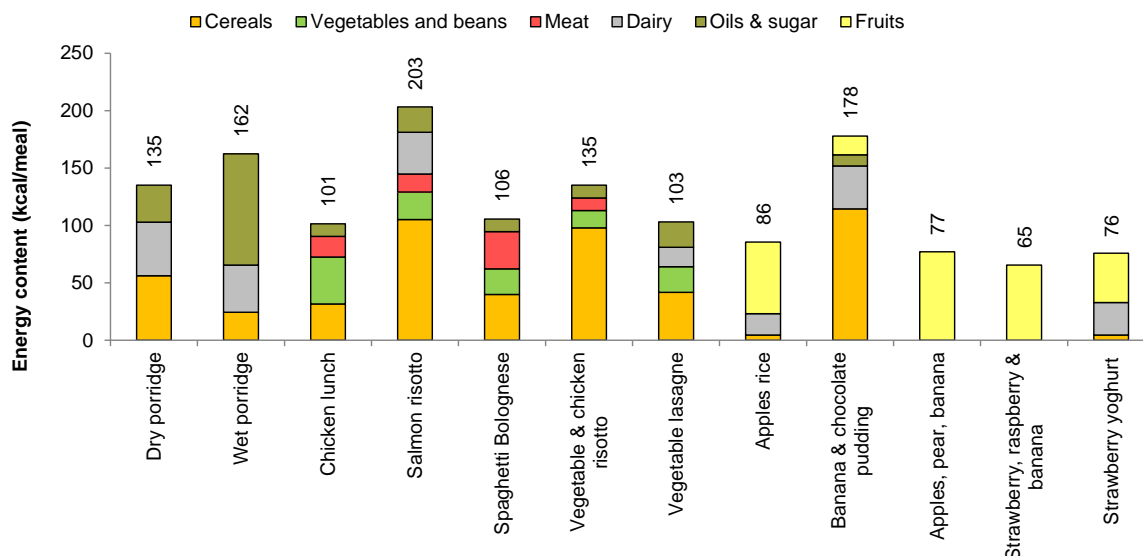


Figure 5 Nutritional value of individual meals [125 g/meal]

The energy content in the weekly menus considered here and summarised in Figure 6 compares reasonably well with the above guidelines, with a variation of $\pm 15\%$. The only exception is the dairy-free diet with a shortfall in calories of 35%. However, this can be supplemented by solid food complements, alongside milk or formula, to meet the baby's nutritional needs.

Regarding the environmental impacts of the diets with respect to their calorie content, it can be observed in Figure 6 for the example of GWP that the dairy-free diet provides the lowest weekly calorie intake but leads to the highest GWP. Consequently, the environmental impacts of the dairy-free diet per kcal are higher than for the other three diets (Table 3). The same trend is found for the analysis based on the mass of the meals (Figure 3). The reason for this is the previously-mentioned reliance of the dairy-free diet on meat-based meals, particularly spaghetti Bolognese, which have higher impacts. Therefore, an increased diversity of dairy-free meals in the marketplace, with high nutritional content, may be an area of potential improvement for baby food manufacturers. This could help overcome both the relatively lower calorie intake of a dairy-free diet and the higher environmental impact.

Overall, the pescatarian diet has the lowest impacts for all of the categories when taking into account the calorie content in the meals. The only exception is marine ecotoxicity potential which is the lowest for the vegetarian diet. This is in contrast with the impacts estimated per mass of meals (Figure 3) where the vegetarian and pescatarian diets had similar impacts. However, it should be noted that the pescatarian menu considered in this work is limited to only one type of lunch meal – salmon risotto – which may influence the results. It is recommended that future work considers a wider variety of sea-food meals.

The differences between the omnivore and vegetarian diet are small which was also found in the analysis based on the mass of the meals.

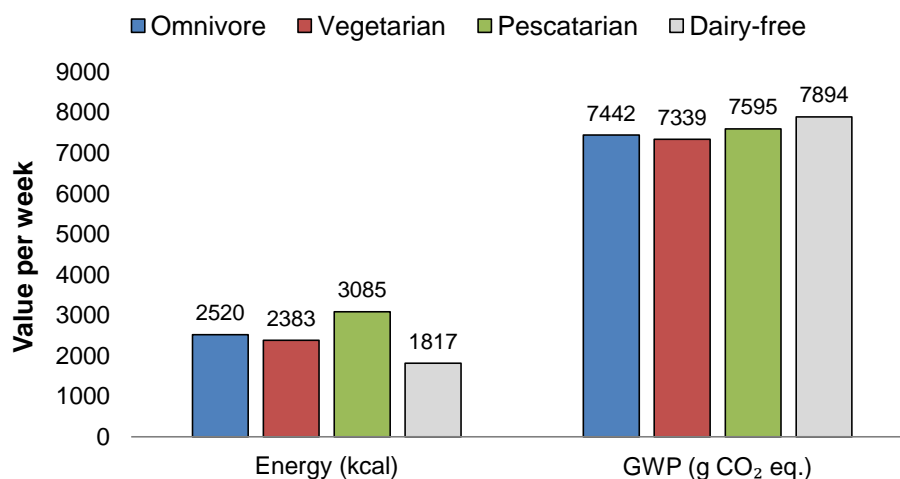


Figure 6 Nutritional content vs global warming potential (GWP) of different diets [Energy content and GWP expressed per baby per week.]

Table 3 Environmental impacts of weekly consumption of baby food for different diets based on nutritional value

Impact per nutritional value	Omnivore	Vegetarian	Pescatarian	Dairy-free
GWP (g CO ₂ eq.)/kcal	2.95	3.08	2.46	4.34
ADP elements (mg Sb eq.)/kcal	0.02	0.02	0.02	0.04
ADP fossil (MJ)/kcal	0.03	0.03	0.03	0.05
AP (g SO ₂ eq.)/kcal	0.02	0.02	0.02	0.02
EP (g PO ₄ eq.)/kcal	0.01	0.01	0.01	0.01
FAETP (g DCB eq.)/kcal	0.52	0.52	0.40	0.82
HTP (g DCB eq.)/kcal	1.90	1.95	1.51	3.08
MAETP (kg DCB eq.)/kcal	3.10	1.95	2.49	5.31
ODP (μg R11 eq.)/kcal	0.26	0.28	0.22	0.43
POCP (mg C ₂ H ₄ eq.)/kcal	1.44	1.50	1.24	1.82
TETP (g DCB eq.)/kcal	0.03	0.03	0.02	0.03

4 Conclusions and recommendations

This paper considered the life cycle environmental impacts that arise from the production and consumption of ready-made baby foods, considering 12 different meals and four types of diet: omnivorous, vegetarian, pescatarian and dairy-free. This is the first time such a study has been carried out for baby foods, providing a basis for the scientific community to build on in this area.

The results showed that, for the majority of the 11 impact categories analysed, lunch meals had the highest impacts and dry porridge and desserts the lowest. Among the lunch meals, spaghetti Bolognese and salmon risotto had the highest impacts and among desserts, strawberry, raspberry and banana as well as apple, pear and banana desserts were environmentally the best options.

The key hotspots across the meals were raw materials and packaging. Manufacturing also played a significant role for global warming potential as well as depletion of fossil resources and the ozone layer due to the fossil fuels used in the process. Overall, meals with more meat and cream were found to have higher impacts so their reduction or substitution offers potential for environmental improvements. It is recommended that this be explored further by the industry via product reformulation, and will also be of interest to consumers concerned with reducing their impacts on the environment.

When the impacts were analysed per mass of baby food consumed weekly, the dairy-free diet had higher impacts than the other three, but the difference among them was relatively small. The only exceptions were human toxicity and marine ecotoxicity, which were notably higher for the dairy-free diet than for the others. The trends changed when the nutritional value was taken into account, with the dairy-free diet exhibiting considerably higher impacts per unit of energy content. In that case, the pescatarian diet became the best option for most impacts. There was little difference between the omnivore and vegetarian diets. However, these results should be interpreted only in the context of the meals considered here as the outcomes may change for other meals and recipes. Consideration of a broader range of these, as well as other diets, such as vegan, should be explored in future work. Moreover, as nutrition is more complex than the amount of meals or calories consumed, future micronutrient assessments would also be valuable. This should also include the exploration of life cycle environmental impacts for a range of functional units in line with the key nutrients provided.

The baby food sector is one component of the broader food sector and shares many common ingredients with adult food products, with key differences lying primarily in processing methods, product size and packaging. Consequently, future work could compare the environmental impacts of baby food to adult foods in order to place the results estimated here in a broader context.

Furthermore, reduction targets specific to each of the impact categories could be defined relative to the environmental performance of individual meals or diets and used by manufacturers or policy makers to pursue sustainability improvements. Finally, future studies should consider the economic and social sustainability of baby food, to complement the environmental sustainability considered in this work.

Acknowledgements

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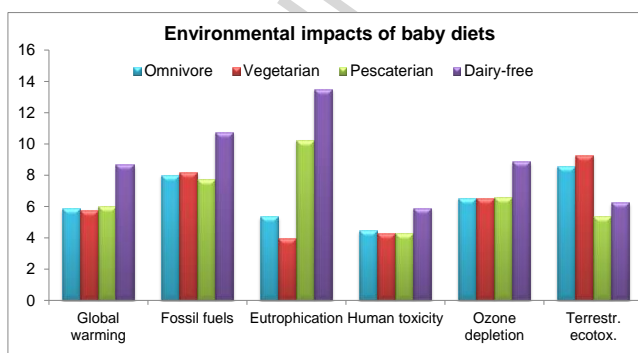
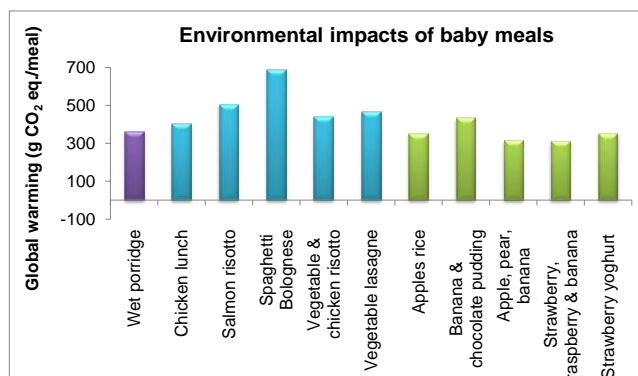
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Graphical Abstract



Highlights

- Spaghetti Bolognese has the highest impacts of 12 ready-made baby foods.
- Fruit-based meals have the lowest impacts.
- Raw materials, manufacturing and packaging are the main hotspots.
- Omnivorous, pescatarian and vegetarian baby diets have similar impacts.
- The dairy-free diet is significantly worse due to higher reliance on meat.

ACCEPTED MANUSCRIPT

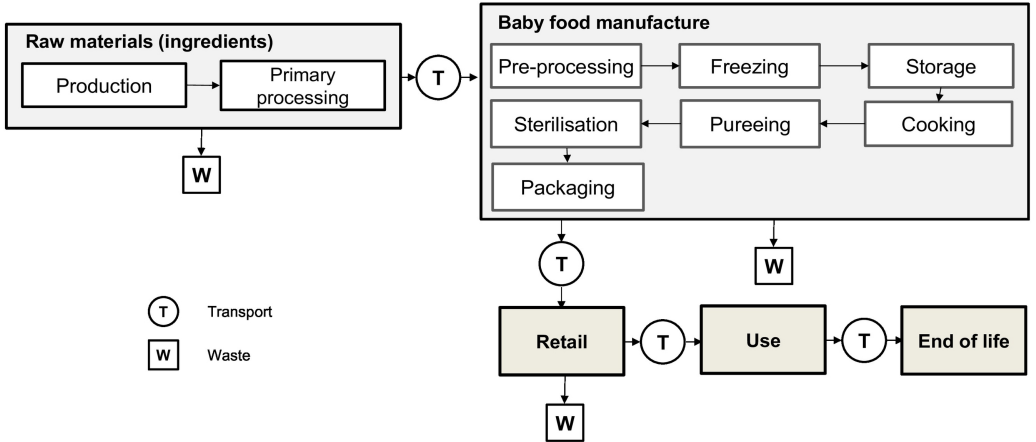


Figure 1

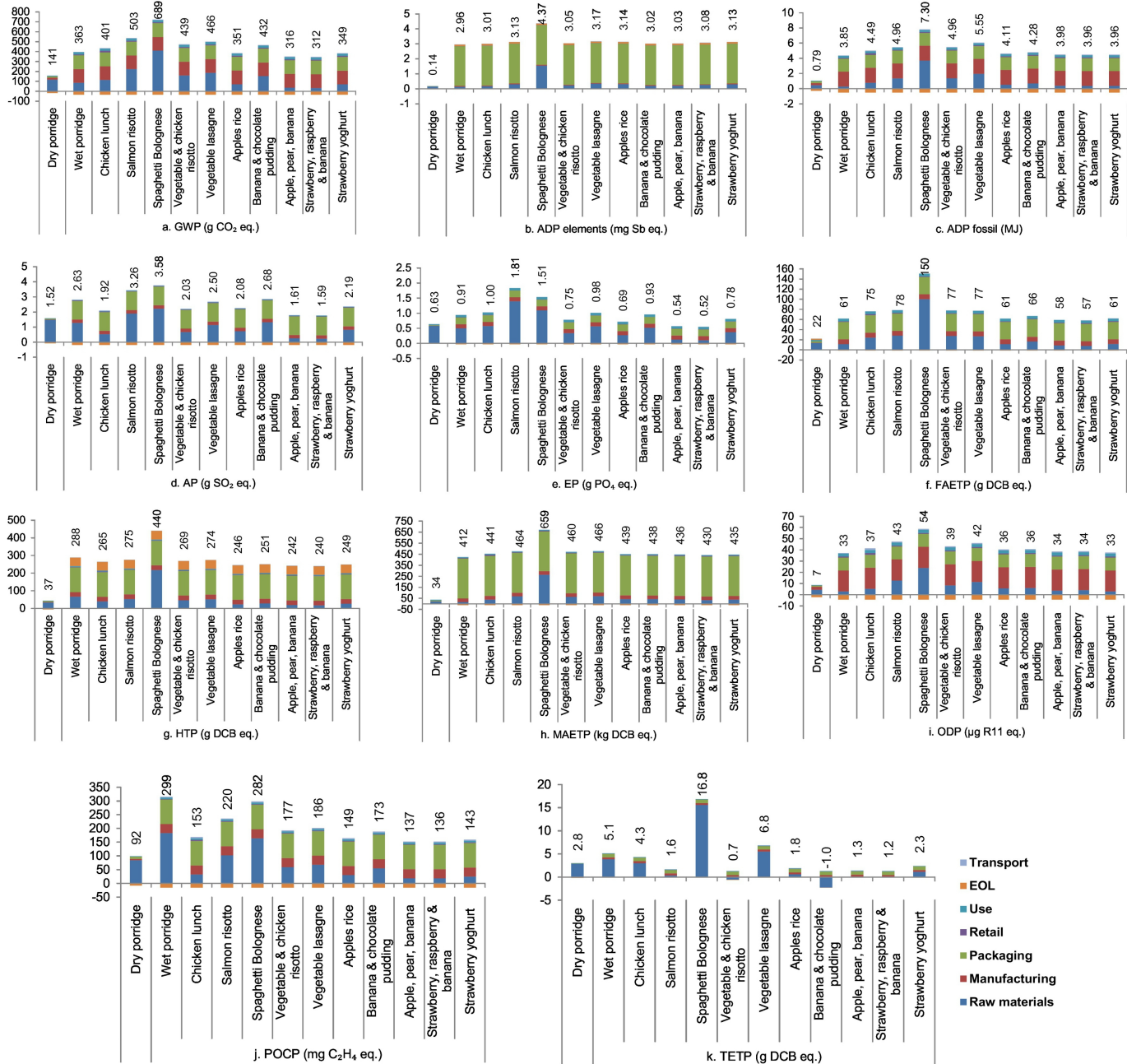


Figure 2

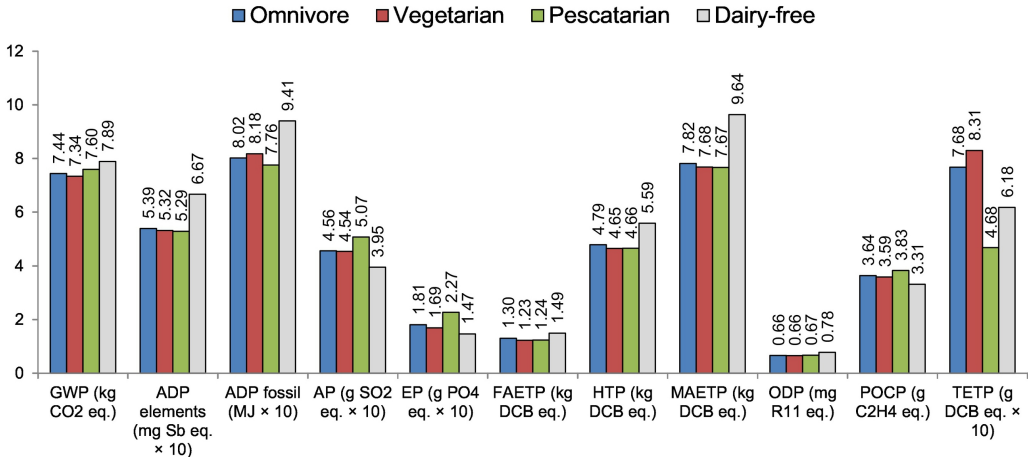


Figure 3

■ Cereals
 ■ Veg. & beans
 ■ Meat
 ■ Dairy
 ■ Oils & sugar
 ■ Fruits

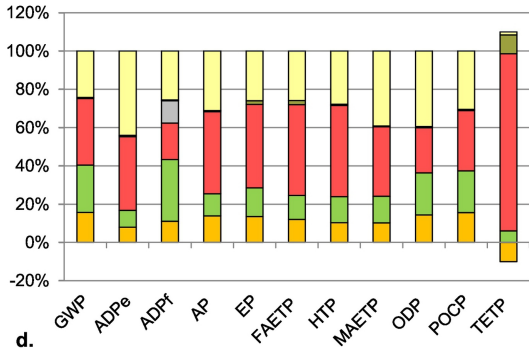
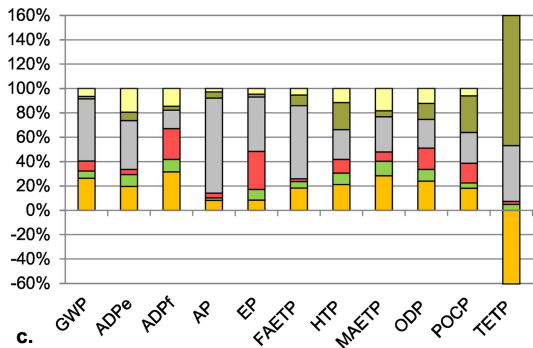
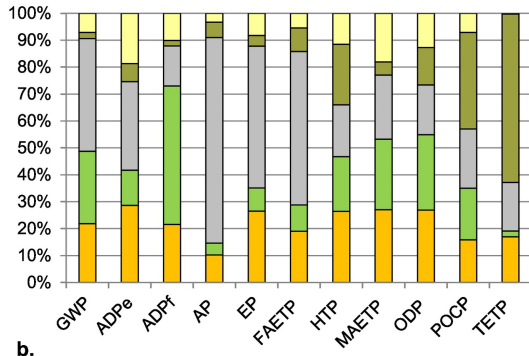
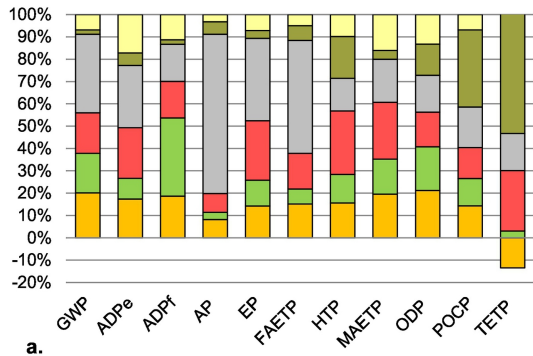


Figure 4

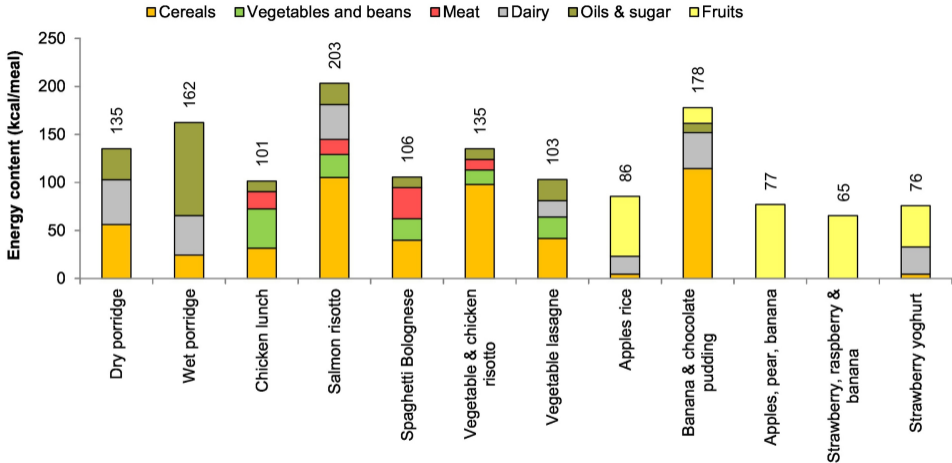


Figure 5

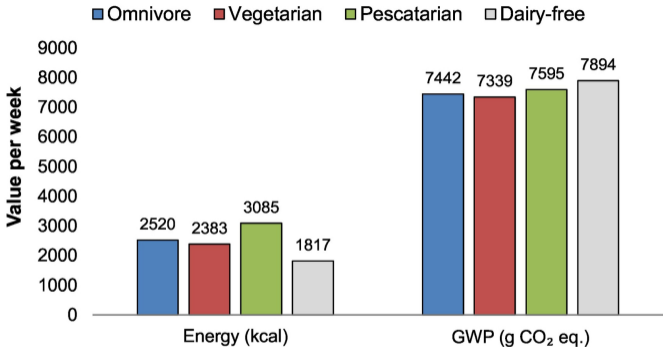


Figure 6