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Comparison of environmental impacts of individual meals - Does it really make a difference to choose plant-based meals instead of meat-based ones?

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ABSTRACT

More than one third of global greenhouse gas emissions (GHG) can be attributed to our food system. Limiting global warming to 1.5° or 2 °C will not be possible without reducing GHG emissions from the food system. Dietary change at the meal level is of great importance as day-to-day consumption patterns drive the global food production system. The aim of this paper was to assess the life cycle environmental impact of a sample of meals from different cuisines (chilli, lasagne, curry and teriyaki meals) and their meat-based, vegetarian, vegan, and whole-food vegan recipe variations. The environmental impacts (global warming, freshwater eutrophication, terrestrial acidification and water depletion potential) of 13 meals, made with 33 different ingredients, were estimated from cradle to plate using Life Cycle Assessment (LCA). Results showed that irrespective of the type of cuisine, the plant-based version of meals (vegan and whole-food vegan) had substantially lower environmental impacts across all impact categories than their vegetarian and meat-based versions. On average, meat-based meals had 14 times higher environmental impact, while vegetarian meals had 3 times higher environmental impact than vegan meals. Substantial reductions in the environmental impacts of meals can be achieved when animal-based ingredients (e.g., beef, cheese, pork, chicken) are replaced with whole or minimally processed plant-based ingredients (i.e., vegetables, legumes) in recipes. Swapping animal-based meals for plant-based versions, and preferably transitioning to plant-based diets, present important opportunities for mitigating climate change and safeguarding environmental sustainability.

1. Introduction

Current food production and consumption patterns are major drivers of climate change and environmental degradation (IPCC, 2014; UNEP et al., 2016). The global food system is responsible for approximately one third (34%) of global anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021), ~32% of global terrestrial acidification and ~78% of eutrophication (Poore and Nemecek, 2018). Furthermore, 70% of freshwater and 50% of habitable land is used for agriculture (Ellis et al., 2010; FAO, 2011).

In particular, the impact of animal agriculture on the environment is staggering. Approximately half of the GHG emissions of the food system comes from animal agriculture (Gerber et al., 2013; Parks, 2007). A recent study (Xu et al., 2021) estimates that as much as 57% of global GHG emissions from food production come solely from the production of animal-based foods, while 29% come from the production of plant-based foods and 14% from other utilisations. Livestock production also occupies a disproportionally large amount of land, and it is the primary driver of land use change, biodiversity loss, deforestation and species extinction (Coimbra et al., 2020; IPBES, 2019; Pereira et al., 2010). Of all agricultural land, almost 80% is used for grazing livestock and growing crops for animal feed, and only about 20% is used to grow crops for human consumption (Parks, 2007). Yet, meat and dairy only provide 18% of global calorie supply and 37% of total protein supply (Poore and Nemecek, 2018).

According to Clark et al. (2020) even if all non-food system GHG emissions were halted immediately, emissions from the food system alone could prevent the achievement of the Paris Agreement (i.e., limiting global temperature increase to 1.5° or 2 °C above preindustrial

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Acronyms

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
FU	Functional Unit
GHG	Greenhouse gas
GWP	Global Warming Potential
FEP	Freshwater Eutrophication Potential
TAP	Terrestrial Acidification Potential
WDP	Water Depletion Potential
WF	Whole-food

levels). Increasing efficiencies in food production (e.g., altering management practices, limiting the use of nitrogen fertilisers, pesticides and other inputs) and reducing food waste along the supply chain are important strategies to mitigate the negative environmental impacts of the food system (Clark et al., 2020). However, the ability of these strategies to reduce environmental impacts is limited and therefore changes in dietary patterns must also be addressed rapidly (Davis et al., 2016; Garnett, 2011; Hayek et al., 2021).

The extent to which different diets affect environmental sustainability is relatively well-researched and has been shown to be substantial (Aleksandrowicz et al., 2016; Hallström et al., 2015). Despite the robust scientific evidence suggesting that whole-food, plant-based diets centred around the consumptions of whole-foods (e.g., vegetables, legumes, fruits, whole grains, nuts and seeds) have both environmental and public health benefits (Dinu et al., 2017; Sabaté and Soret, 2014; Springmann et al., 2016; Tilman and Clark, 2014), only 8 percent of the global population follows a meat-free (i.e., vegetarian) or plant-based (i.e., vegan) diet (Ipsos, 2018). While some do not perceive any barriers and find it effortless to transition to plant-based eating (Lea et al., 2006), others struggle for several reasons (Alcorta et al., 2021; Stubbs et al., 2018). Lack of awareness of the relationship between meat consumption and climate change, the perception that individual meat consumption plays a minimal role in climate change and environmental degradation, and the resistance to reduce personal meat consumption for social, personal or cultural reasons are some of the most commonly perceived barriers to change (Macdiarmid et al., 2016). Promoting dietary change at the meal level and communicating the environmental impacts of different types of meals therefore could be an important strategy to address these barriers to change and facilitate the transition towards plant-based eating patterns at the meal level.

The aim of this paper was to better understand the magnitude of environmental impacts associated with different meal choices, and to show the difference in environmental impacts of choosing a plant-based version (i.e., vegan) of a meal instead of its animal-based version (i.e. vegetarian or meat-based). In this study, the life cycle environmental impacts of four commonly consumed meals (chilli, lasagne, curry and teriyaki) and their meat-based, vegetarian, vegan, and whole-food vegan recipe variations were assessed using Life Cycle Assessment (LCA).

To date, only a few studies have analysed and compared the environmental impacts of recipe variations of the same meals: e.g., spaghetti bolognaise with beef vs vegetarian spaghetti bolognaise (Clune, 2019), pork vs bean stew (San Miguel and Ruiz, 2021), dinner with meat vs meat-alternative (Hanssen et al., 2017), pork chop vs pea burger (Davis et al., 2010), or pork tenderloin vs vegetarian Quorn alternative (Sturtewagen et al., 2016). These studies and other published LCA studies e.g. (Schmidt Rivera et al., 2014; Cooreman-Algoed et al., 2020; De Laurentiis et al., 2017; Saarinen et al., 2012; Saxe et al., 2018), focus on comparing meat-based meals (e.g., beef, lamb, pork, chicken), fish-based meals and vegetarian meals, without making a clear distinction between different types of meatless meals (e.g., vegetarian, vegan and whole-food vegan meals). Although 'vegetarian', 'vegan' and 'whole-food vegan' meals are all meat-free meals, these terms have different meanings and are not interchangeable (see section 2.2). The lack of distinction between different types of meatless meals can lead to inconsistent results, and thus a more accurate classification of meals is needed (Takacs and Borrion, 2020). A few studies e.g., Pulkkinen et al. (2016) and van de Kamp and Temme (2018) include and discuss specifically vegan or plant-based meals, but to the best of the authors' knowledge, no LCA studies have compared the vegan version of a meal with its vegetarian or meat-based version. Furthermore, no studies have included whole-food vegan meals in their analysis. As processed vegan foods such as vegan meat and dairy alternatives are becoming more available, it is increasingly important to make a distinction between processed vegan and whole-food vegan meals.

The novelty of this research lies in not only analysing different recipe variations of the same meals (i.e., vegan, vegetarian or meat-based version) but also making a clear distinction between different types of meatless meals and analysing vegetarian, vegan and whole-food vegan meals separately, instead of together under the umbrella term of 'vegetarian' as done in previous research. With this new classification, it is possible to get a more accurate sense of which types of meals have the lowest environmental impact. Also, by analysing different recipe variations of the same meal, it is possible to determine whether it is the recipe variation, the ingredients, the cuisine, the preparation mode or the origin of ingredients and their transportation that most influences the environmental sustainability of meals.

This research compliments existing research on the environmental impacts of meals and contributes to our knowledge of understanding the differences in environmental impacts between animal-based and plant-based meals. The results of this study will provide evidence-based information for both consumers and food service providers on how to mitigate climate change and reduce the negative environmental impacts arising from individual meal and food choices. Furthermore, the outcome will also aid meal planning and help develop procurement policy in the food service sector. By knowing the environmental impact of different types of meals and their recipe variations, consumers and food service providers can make more informed decisions about what kind of meals to prepare, offer or consume on a daily basis.

2. Method

2.1. Life Cycle Assessment approach

In this study, Life Cycle Assessment (LCA) was used to analyse the environmental impact of different types of meals. LCA is a comprehensive, internationally standardised method for assessing the environmental impact of a product or system over its whole life: from production, distribution through consumption and disposal. It has the potential to quantify relevant resource use and related emissions and environmental impacts of a particular product or service throughout its entire life cycle. Since the main goal of this research was to estimate the direct environmental impact of different types of meals, an attributional LCA approach was adopted following the international standards of ISO 14040/14044 (ISO, 2006a & b).

2.2. Goal and scope

The main goal of this study was to assess the environmental impacts of different types of meals offered in the lunch service at an institutional food service establishment in London, UK over their whole life cycles. The LCA approach was used to identify environmental impact hotspots in the meal life cycles. Thirteen meals, made with 33 different ingredients, were evaluated. Meals included in the analysis were: lasagne, curry, chilli and teriyaki meals (Table 1).

Within each meal category, the following recipe variations were compared: meat-based, vegetarian, vegan, and whole-food vegan. Meat-

Table 1
Meals and their animal- and plant-based recipe variations included in the analysis.

	Animal -based		Plant-based	
	Meat-based	Vegetarian	Vegan	Whole-food vegan
Lasagne	Beef lasagne	Vegetarian Quorn & spinach lasagne	Vegan mince & spinach lasagne	Whole-food vegan lasagne with lentils & vegetables
Chilli	Chilli con carne (with beef)	Vegetarian Quorn mince chilli	–	Whole-food vegan chilli with vegetables
Curry	Thai green chicken curry	–	Vegan Thai green curry	Whole-food vegan Thai green curry
Teriyaki	Chicken teriyaki	–	Vegan tofu teriyaki	Whole-food vegan teriyaki with tempeh & vegetables

based recipes are normally the "traditional" version of the meal and may include all kinds of animal-as well as plant-based ingredients. Vegetarian recipes do not contain any kind of meat but may contain other animal-based ingredients such as eggs and dairy. Vegan recipes exclude all animal derived ingredients and therefore contain no meat, fish, dairy, or eggs. The difference between vegan and whole-food vegan recipes is that whole-food vegan recipes are made with whole, minimally processed ingredients of plant origin, and thus do not contain any processed and/or refined ingredients such as added sugars, refined grains, processed oils and processed vegan meat and dairy alternatives. Vegan recipes on the other hand may include all types of processed vegan ingredients. A summary of the main differences between the ingredients used for each recipe variation is provided in Table 2.

2.3. Functional unit

In this study, it was assumed that all meals served by the food service provider were nutritionally adequate and had the same function: to provide lunch (i.e., a meal) for the customer. The functional unit (FU) therefore was a single meal, with impact calculated from cradle to plate. While using nutrition-based FU can be useful, in this study a single meal was considered more appropriate for the following reasons:

1. Customers go to a food service provider with the intention to choose a meal for lunch (e.g., a lasagne) and not to consume a certain amount of calories, protein or other nutrients, which are usually suggested as a nutrition-based FU in food LCA studies.

Table 2
The key differences between meat-based, vegetarian, vegan and whole-food, plant-based meals.

Ingredients	Animal-based		Plant-based	
	Meat-based	Vegetarian	Vegan	Whole-food vegan
Meat	✔	✘	✘	✘
Fish and Seafood	✔	✘	✘	✘
Eggs and dairy	✔	✔	✘	✘
Processed oils	✔	✔	✔	✘
Processed and refined foods (meat and dairy substitutes, added sugars, refined grains etc.)	✔	✔	✔	✘
Whole grains	✔	✔	✔	✔
Fruits and vegetables	✔	✔	✔	✔
Legumes	✔	✔	✔	✔
Nuts and seeds	✔	✔	✔	✔
Herbs and spices	✔	✔	✔	✔

2. According to the position of the Academy of Nutrition and Dietetics, an appropriately planned vegan diet, which is made up of vegan meals such as the ones included in this analysis, is healthful and nutritionally adequate (Melina et al., 2016). Therefore, it was assumed that all meals would provide adequate nutrition. To test this assumption, further in-depth analysis of the nutritional quality of meals would be required, however, this was outside the scope of this paper.

Before calculating the LCAs of meals, the environmental impacts of individual ingredients ($n = 33$) used in the recipes were calculated based on 1 kg of ready-to-use ingredient. A wet mass-based functional unit rather than a nutrition-based functional unit was used in the LCA of ingredients too because in recipes the quantities of ingredients are normally specified by wet mass (i.e., weight) and not by calories or nutrients. A mass-based FU not only allows for the calculation of the environmental impacts of recipes, but it also helps food services providers and consumers better understand the contribution of different ingredients to the overall environmental impact of meals and recipes.

2.4. System boundaries

The stages included in the system boundary are agricultural produce and ingredient production, distribution, storage and meal preparation. Fig. 1 shows the system boundary, using the chilli recipes as an example. Note that the system boundary is the same for all the other meals, the only difference is the ingredients in the ingredient production stage as each recipe has a different combination of ingredients. A brief description of the main stages is provided below.

2.4.1. Production of ingredients

The types and quantities of ingredients used in each recipe were obtained from recipe cards that were provided by the institutional food service provider. Ingredients weighing less than 1% of the total weight of each recipe (e.g., spices, salt, chili pepper, garlic) were excluded from the LCA of meals. After the exclusion of these ingredients, the LCAs of 33 ingredients were carried out and used in the LCAs of the meals. For compound ingredients, i.e., ingredients composed of more than one ingredient (e.g., vegan meat and dairy alternatives and sauces such as soy sauce), the LCA of the components of the compound ingredient was carried out then summed according to the quantities needed to make the compound ingredient.

The following inputs were considered for the production of each ingredient: fertilizers (nitrogen, phosphorus and potassium), pesticides, water and energy use (both electricity and heat where appropriate), agricultural machinery use (e.g., for tillage, sowing, fertilising, spraying of plant protection products and combine harvesting), diesel used for field operations, and animal feed production, and the associated fertilisers, fossil fuels and other resource use.

2.4.2. Transport and distribution

Transportation distances of ingredients from site of production to site of processing (when relevant) and to the central kitchen were included in the distribution stage. Information on the countries of origin of each ingredient were collected from the food service provider during site visits ($n = 2$). The transportation modes (road and sea) assumed for each ingredient were based on the information about the origin of production and the specific temperature requirements of the ingredients. For the calculation of freight distances, it was assumed that ingredients were transported from capital to capital (i.e., from the country of origin of production to London). An additional a "local short distance" of 100 km was added to cover any transportation that may have occurred from farm gate to the processing or distribution centre. It was assumed that, in the UK and Europe, only heavy goods vehicles (HGV) were used for transportation of food. Non-perishable items from overseas were assumed to be shipped by cargo containers (see Supplementary

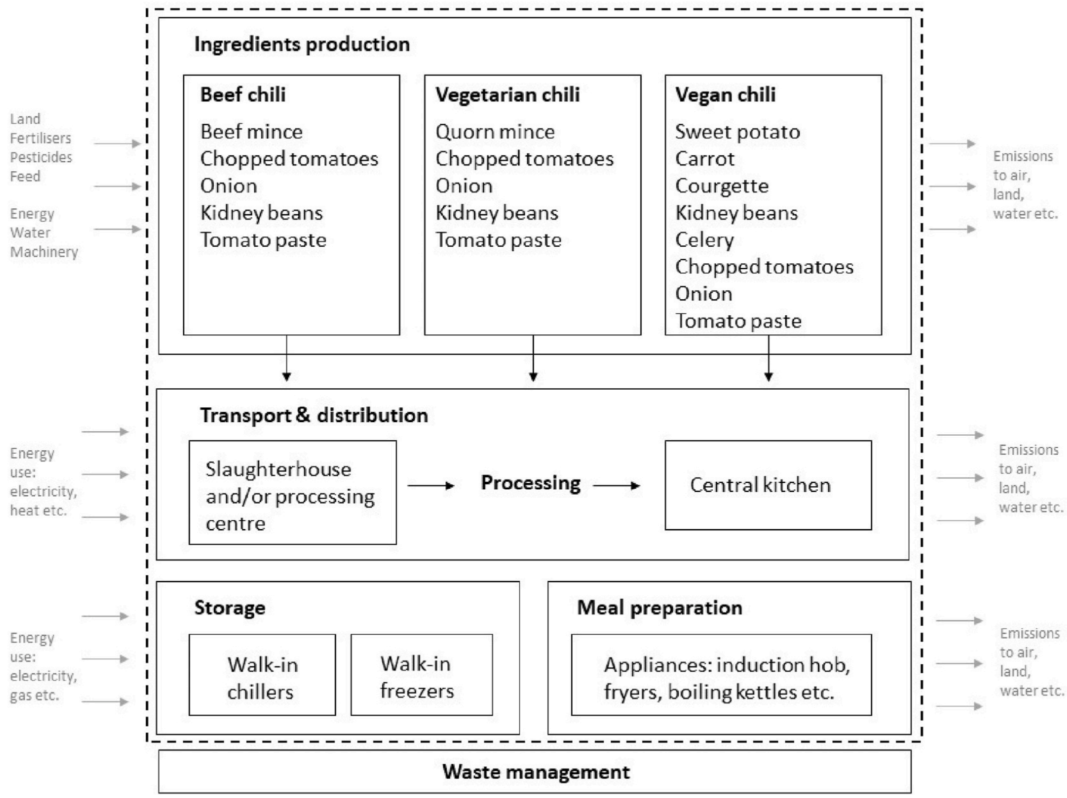

Fig. 1. System boundary used in this study for the example of chilli.

Information Table 3). Distances for road freight were calculated using google maps. Sea freight distances were calculated using the online tool by Sea-distances.org (2019). Road and sea distances used in this study can be found in Supplementary Information Table 4.

2.4.3. *Processing*

Vegetable, dairy and meat processing were included in the system boundary. The following processing steps were considered for vegetables: washing, sorting, peeling, slicing/cutting, blanching (belt blancher with water cooling), freezing and canning. Meat processing included beef, pig and poultry processing, and it was considered up until the stage of getting cut-up, deboned and chilled meat as a final product.

2.4.4. *Storage*

The energy consumption of walk-in chillers and freezers used at the central kitchen for storing ingredients before preparation was included in the system boundary. Due to the lack of primary data available, the total energy consumption of the walk-in chiller was assumed to be 13.81 kWh per day, and the total energy consumption of the walk-in freezer was assumed to be 39.17 kWh per day (Mudie et al., 2016).

2.4.5. *Preparation (cooking)*

Primary data about the energy consumption of appliances used for the preparation of meals (e.g., induction hob, fryers, boiling kettles) were collected during site visits, and can be found in Supplementary Information Table 6. The energy consumption of each appliance was calculated from the power rating (in Watts) stated in each equipment's specifications multiplied by the estimated time of use per meal (in hours). Assumptions of cooking and baking times for each meal were based on the information and cooking instructions provided in the recipe cards (Supplementary Information Table 5).

2.4.6. *Waste*

Waste (both food and general waste) and packaging of ingredients were excluded from the system boundary along with energy use associated with lighting, ventilation and dishwashing in the kitchen due to limited primary data availability for these aspects for the specific case study.

2.5. *Life cycle inventory and data sources*

The Life Cycle Inventory (LCI) provides an inventory of the input and output flows for a product system. Primary data on meals and recipes were collected from the food service provider through semi-structured interviews ($n = 5$) and site visits ($n = 2$). The composition of meals and the quantities of ingredients used in each recipe are summarised in Table 3. Key data sources for the LCI are summarised in Table 4. In the present study, foreground data (i.e., inputs for ingredient production and processing) were sourced from the literature and from the Ecoinvent 3.6 database (2019) (see Supplementary Information Table 1), while background data (e.g., information for energy and transport and materials used in the production stage such as pesticide and fertiliser production came from the Ecoinvent 3.6 database (2019), (Supplementary Information Tables 7 and 8).

2.6. *Impact categories and life cycle impact assessment*

The ReCiPe midpoint method (Goedkoop et al., 2009) was followed for the life cycle impact assessment, using the hierarchist model. For each meal the following environmental impact categories were considered: global warming potential (GWP100), freshwater eutrophication (FEP), terrestrial acidification potential (TAP100) and water depletion (WDP). These impact categories were selected as they are the most relevant for the assessment of food and meals (Pernollet et al., 2017). Land use is also an important impact category for food LCA as it is a key driver of global biodiversity loss through habitat loss and fragmentation (Benton et al., 2021). However, quantifying the impacts of food production and consumption on land use and biodiversity remains

Table 3
Composition of the meals and the quantities of ingredients used in each meal. WF = Whole-food.

Ingredients (g/meal)	Beef lasagne	Vegetarian lasagne	Vegan lasagne	WF vegan lasagne	Beef chilli	Vegetarian chilli	WF vegan chilli	Chicken curry	Vegan curry	WF vegan curry	Chicken teriyaki	Vegan teriyaki	WF vegan teriyaki
Beef	120	–	–	–	120	–	–	–	–	–	–	–	–
Chicken	–	–	–	–	–	–	–	140	–	–	120	–	–
Pork	11	–	–	–	–	–	–	–	–	–	–	–	–
Milk	115	92	–	–	–	–	–	–	–	–	–	–	–
Cheese	30	30	–	–	–	–	–	–	–	–	–	–	–
Flour	11	9	9	–	–	–	–	–	–	–	–	–	–
Meat alternative	–	50	50	–	–	140	–	–		–	–	–	–
Cheese alternative	–	–	20	–	–	–	–	–	–	–	–	–	–
Pasta/noodle	50	50	50	50	–	–	–	–	–	–	80	80	80
Tofu	–	–	–	–	–	–	–	–	–	–	–	100	70
Soy milk	–	–	92	–	–	–	–	–	–	–	–	–	–
Oil/margarine	11	9	9	–	–	–	–	10	5	–	–	6	–
Onions	20	20	20	20	38	30	30	30	63	63	–	–	40
Root Vegetables[a]	11	–	–	11	–	–	110	–	–	40	–	–	50
Other Vegetables[b]	11	20	20	170	–	–	90	–	150	150	–	–	50
Pulses	–	–	–	80	30	50	100	–	–	–	–	–	–
Tomatoes and nightshades[c]	110	120	130	190	106	56	126	–	60	60	–	–	25
Other[d]	–	–	–	–	–	–	–	49	45	30	50	50	15
Total weight of ingredients per meal	499	410	391	510	294	276	456	229	323	343	250	236	330

[a] Root vegetables: carrot, sweet potato.
[b] Other vegetables: celery, spinach, zucchini, cauliflower, broccoli.
[c] Tomatoes and other nightshades: Tomatoes, peppers, aubergines.
[d] Other: coconut milk, sauces (e.g., teriyaki and soy sauce).

Table 4
Summary of key data sources for each life cycle stage.

Life Cycle Stage	Item/parameter	Source
n/a	Recipes and recipe cards	Primary data: semi-structured interviews
Production	Ingredients (inventory data of inputs to produce 1 kg of the ingredient)	Various sources (see Supplementary Information Table 1)
Production	Background data: machinery, pesticide, and fertiliser production	ecoinvent version 3.6 (2019)
Distribution	Distance for road transport	Google Maps
Distribution	Distance for sea freight	Sea-distances.org (2019)
Distribution	Conversion factors for different transport modes: truck, cargo ship etc.	ecoinvent version 3.6 (2019)
Processing	Vegetable processing (washing, sorting, peeling, slicing etc.)	Santonja et al. (2019)
Processing	Margarine processing	Nilsson et al. (2010)
Processing	Pasta processing	Panno et al. (2007)
Processing	Dairy processing	Natural Resources Wales (2014)
Processing	Meat processing	Ladha-Sabur et al. (2019)
Storage	Walk-in chillers and freezers	Mudie et al. (2016)
Preparation	Energy consumption of appliances	Primary data: site visits
All stages	Country specific conversion factors for electricity and heat	BEIS (2020); AIB (2019); ecoinvent version 3.6 (2019)

challenging. While, various models exist, many of them have only been validated for specific case studies and thus are not yet operational in the common LCA practice (Crenna et al., 2019). Due to the differences and the lack of consensus among existing land use models (Curran et al., 2016), land use was not included as an impact category in this study.

2.7. Sensitivity analysis

The results of an LCA study can be affected by several factors, therefore it is important to gain more insight into the robustness and reliability of the results (Goldstein et al., 2016). Sensitivity analysis allows for the assessment of the sensitivity of results to various input parameters and highlights whether data quality needs to be improved (Wei et al., 2015). It can be used to determine which parameters are most influential on the final results and to strengthen the reliability of the results obtained. In this study, after the most contributing life cycle stages and ingredients were identified, a sensitivity analysis was performed to determine how sensitive the results are to changes in different input parameters. A one-at-a-time approach (Heijungs and Kleijn, 2001) was used in which various parameters (see Table 5) were changed one-at-a-time to determine how much a ± 20% change in an input or model parameter would change the results.

3. Results and discussion

This section presents the results of the environmental impacts of the four different types of meals (lasagne, chilli, curry, teriyaki) and their meat-based, vegetarian, and vegan recipe variations. First, the relative difference in environmental impacts between meat-based, vegetarian and vegan meals is presented. Then the relative difference in environmental impacts of recipe variations of the same meals (e.g., impact of meat-based lasagne vs impact of vegan lasagne) are described. The relative difference in environmental impacts between meals is expressed by taking the vegan meal or the vegan recipe variation as the reference value. In sections 3.3–3.6, the results of each impact category will be reported in more detail. Hotspots in the meal life cycle and the reason for the differences in the magnitude of impacts between plant-based and animal-based meals will be discussed.

3.1. Environmental impacts of meals

Fig. 2 shows the environmental impacts of lasagne, chilli, teriyaki and curry meals and their meat-based, vegetarian, vegan and whole-food vegan recipe variations for the four impact categories considered. Irrespective of the type of cuisine, plant-based (vegan and whole-food vegan) meals had substantially lower environmental impacts across all impact categories than their vegetarian and meat-based versions. Of all the meals examined in this study, whole-food vegan meals had the lowest environmental impacts. Vegetarian meals on average had 3 times higher environmental impact (i.e., 3 times higher GWP, FEP, TAP and WDP), while meat-based meals had on average 14 times higher environmental impact than vegan meals (i.e., 14 times higher GWP, 7 times higher FEP, 15 times higher TAP and 19 times higher WDP). However, large differences could be observed between different types of meat-based meals. The impact of meals made with beef was 32 times higher, while the impact of chicken meals was 6 times higher than that of whole-food vegan meals.

When comparing the relative difference in environmental impacts of recipe variations of the same meals (e.g., beef lasagne vs vegan lasagne), the following results emerged. The beef lasagne had on average 17 times higher environmental impact than the vegan lasagne (i.e., 15 times higher GWP, 7 times higher FEP, 20 times higher TAP and 25 times higher WDP). The beef chilli had 39 times higher environmental impact than the vegan chilli (i.e., 28 times higher GWP, 15 times higher FEP, 28 times higher TAP and 85 times higher WDP). The chicken curry had 14 times higher environmental impact (i.e., 7 times higher GWP, 6 times higher FEP, 4 times higher TAP and 38 times higher WDP) than the vegan curry, while the chicken teriyaki had 4 times higher environmental impact (i.e., 4 times higher GWP, 4 times higher FEP, 2 times higher TAP and 5 times higher WDP) than the plant-based teriyaki.

Fig. 2 also shows the contribution of different life cycle stages to the overall environmental impacts of meals. The agricultural and ingredient production stage was a hotspot in the meal life cycle, and the single biggest contributor to the environmental impacts of meals. Emissions from the transportation stage, along with processing, storage and preparation, made relatively small contributions to the overall environmental impacts of most meals. Whole-food vegan meals had the lowest emissions from the processing stage, while meat-based meals had the highest emissions from processing. On the other hand, vegan meals had the highest emissions form the transport stage, while meat-based meals had the lowest. This can be explained by the fact that in this study meat and dairy were sourced locally (from the UK), while vegetables and other plant-based ingredients were mostly sourced from Europe and overseas (see Supplementary Information Table 1 for origin of ingredients) and thus had higher food miles associated with them. Nevertheless, the overall environmental impacts of vegan meals made with a mix of local and imported ingredients remained substantially lower than that of meat-based meals, which were predominantly made with locally sourced ingredients.

The fact that the transportation stage was not a major contributor to the environmental impacts, which was also found by e.g., San Miguel and Ruiz (2021), refutes the idea that using local ingredients always makes meals more sustainable. While local food systems can have several economic, social and environmental benefits (Enthoven and Van den Broeck, 2021), using local ingredients does not automatically make meals more environmentally sustainable unless the transportation stage is responsible for a large share of the environmental impacts. The environmental impact of ingredients, and thus meals, could be higher if vegetables and other imported ingredients used in the recipes were transported by air and not by sea or road as assumed in this study. According to Frankowska et al. (2019) the impacts of air-freighted fresh vegetables could be around five times higher than of those produced domestically. However, only a small proportion of vegetables imported from outside the UK are air-freighted; these normally include fresh green beans, peas and asparagus. Other vegetables, including the ones that were also used in thesrecipes included in this study, are either transported by road or shipped by sea.

3.2. Influence of ingredients

The LCA showed that it is not the type of cuisine that determined the magnitude of environmental impact of meals but rather the ingredients used in recipes. It did not matter whether it was Italian cuisine (pasta dishes), Asian cuisine (teriyaki meals) or Indian cuisine (curry meals), meals made with animal-based ingredients, including vegetarian meals that contained considerable amounts of dairy and cheese (i.e., vegetarian lasagne), consistently had considerably higher environmental impacts across all impact categories than their plant-based versions.

This is because there are large and systematic discrepancies among the environmental impacts of ingredients used in meals. As shown in Fig. 3, animal-derived ingredients (e.g., beef, cheese, pork and chicken) had the highest environmental impact per kilogram of ingredient across all impact categories. In contrast, vegetables, legumes and unprocessed whole foods consistently had the lowest environmental impact across all impact categories. Vegetables and other whole-foods, even when imported, had considerably smaller environmental impact than locally sourced meat, dairy and other animal-based ingredients. Processed plant-based ingredients (e.g., refined oils, margarine and vegetarian and vegan meat substitutes etc.) also had lower environmental impact than meat, but they had higher impact than whole-foods.

These results are in agreement with the findings of other studies, which also show that meat (e.g., beef, pork, chicken) and other animal-based ingredients (e.g., cheese, milk) have considerably higher environmental impact than plant-based products (e.g., Nordborg et al., 2017; Poore and Nemecek, 2018) and are the main contributors to most environmental impact categories (e.g., Hanssen et al., 2017; San Miguel and Ruiz, 2021).

3.3. Global warming potential of meals

The global warming potential (GWP) of meals ranged between 0.11 and 5.78 kg CO_2-eq per meal. Whole-food vegan meals had the lowest GWP of all meals, with an average of 0.19 kg CO_2-eq. Vegan meals had the second lowest GWP, with an average of 0.25 kg CO_2-eq. The average GWP of vegetarian meals was 0.68 kg CO_2-eq, while the average GWP of meat-based meals were 3.07 kg CO_2-eq.

3.3.1. Global warming potential of lasagne meals

The GWP of the different lasagne recipes are shown in Fig. 4. The vegan and the whole-food vegan lasagnes had the lowest GWP (0.37 kg CO_2-eq and 0.26 kg CO_2-eq respectively). In contrast, the beef lasagne had the highest GWP (5.78 kg CO_2-eq), where beef was the main contributor with 85%, followed by cheese and milk with 7% and 4% respectively. This is in alignment with the results of Schmidt Rivera and Azapagic (2019) who estimated the GWP of a classic lasagne to be 5 kg CO_2-eq, with beef being the main contributor with 83%. In our study enteric fermentation and methanogenic emissions from the rumen (55%), manure management (22%) and the use of fertilisers (17%), in particular N fertilisers, for feed production were the main contributors responsible for the high GWP of beef, as also found by previous LCA studies e.g. (Asem-Hiablie et al., 2019; Herrero et al., 2013; Mazzetto et al., 2015). The GWP of the vegetarian lasagne was 1/6th of the beef lasagne (0.92 kg CO2 eq), with cheese and milk as the main contributors, with 49% and 20% respectively. Nevertheless, when compared to the plant-based lasagnes, the vegetarian lasagne still had 2.5 times higher GWP than the vegan lasagne and 3.5 times higher GWP than the whole-food vegan lasagne.

3.3.2. Global warming potential of chilli meals

Similar trends could be observed for the chilli recipes. As shown in Fig. 5, the whole-food vegan chilli had the lowest GWP (0.18 kg CO_2-eq) of all chilli recipes. The vegetarian chilli had 2.4 times higher GWP (0.44 kg CO_2-eq), while the beef chilli had 27.6 times higher GWP (4.97 kg CO_2-eq) than the vegan chilli. Beef again was the biggest contributor in the beef chilli, responsible for 98% of the GWP, while vegetarian Quorn mince was responsible for 89% of the GWP of the vegetarian chilli recipe.

3.3.3. Global warming potential of teriyaki meals

For the teriyaki meals the differences between animal- and plant-based recipes were not as striking as they were for the lasagne and chilli meals. Nevertheless, a fourfold difference could be observed between the GWP of chicken- and vegan (whole-food) teriyaki recipes. As shown in Fig. 6, the whole-food vegan teriyaki had the lowest GWP (0.21 kg CO_2-eq), followed by the vegan teriyaki with a slightly higher GWP (0.27 kg CO_2-eq). The chicken teriyaki had 3.7 times higher GWP (0.78 kg CO_2-eq) than the whole-food vegan teriyaki, with chicken contributing 79% of GWP of the meal. Feed for chickens, in particular soybean and maize grain were the biggest contributors to the GWP of chicken meat, responsible for 95% of the impacts, which is in agreement with previous LCA studies on chicken meat production e.g. (Cesari et al., 2017; Prudêncio da Silva et al., 2014; Wiedemann et al., 2017).

3.3.4. Global warming potential of curry meals

Fig. 7 shows the GWP of the different curry recipes. Again, plant-based curry recipes had the lowest GWP. The GWPs of both the vegan and the whole-food vegan curries were similar (0.11 kg CO_2-eq). In contrast, the chicken curry had 7 times higher GWP (0.77 kg CO_2-eq) than the plant-based curries. Again, chicken was the main contributor, responsible for 94% of the GWP of the chicken curry.

The trends were similar for the rest of the impact categories, therefore the results for those impact categories will only be described briefly in the upcoming sections.

3.4. Freshwater Eutrophication Potential

As shown in Fig. 2, vegan meals had the lowest Freshwater Eutrophication Potential (FEP). Vegetarian meals (i.e., vegetarian lasagne and vegetarian chilli) and chicken meals had similar FEP, about 4 times higher FEP than that of whole-food vegan meals. Meat-based meals (i.e., beef lasagne, beef chilli, chicken curry and chicken teriyaki) had the highest FEP, on average 9 times higher than that of whole-food vegan meals. When compared to vegan meals, meat-based meals had 6 times higher FEP and vegetarian meals had 3 times higher FEP than vegan meals made with processed ingredients (i.e. meat- and dairy substitutes). The production stage was again dominant, contributing on average 67% to the FEP of meals, followed by processing (12%), transportation (6%), storage (9%) and preparation (6%).

3.5. Terrestrial acidification potential

Vegan meals consistently had the lowest Terrestrial Acidification Potential (TAP), while beef lasagne and beef chilli had the highest TAP, followed by vegetarian and chicken meals. The TAP of vegetarian meals was 3 times higher, and the TAP of meat-based meals was 16 times higher than that of the whole-food vegan meals. For this impact category, the production of ingredients was again a hotspot, contributing on average 67% to acidification, followed by transport with 20%, processing with 6% and storage (4%) and preparation (3%). Fertiliser production and diesel burnt in agricultural machinery caused most of the impacts of vegetable production, while for meat production, it was manure and the production of animal feed (e.g., through the use of fertilisers and diesel burnt in agricultural machinery) that contributed the most to TAP.

3.6. Water depletion potential

Meals made with animal-derived ingredients had the highest Water Depletion Potential (WDP), followed by vegetarian and vegan meals. Whole-food vegan meals had the lowest WDP of all meals. Meat-based meals had 34 times higher WDP than whole-food vegan meals and 14 times higher WDP than vegan meals. The vegetarian meals had 6 times higher WDP than whole-food vegan meals, and 2 times higher WDP than processed vegan meals. The production stage was the single most relevant life cycle stage contributing to 84% to WDP. The contribution of processing was 5%, while storage, transportation and preparation contributed 3%, 4% and 3% respectively.

3.7. Sensitivity analysis

The results of the sensitivity analysis showed that the environmental impacts are most sensitive to changes in the amount of ingredients used in recipes that contribute the most to environmental impacts (e.g., meat). For example, when reducing the amount of meat in recipes by 20%, a 15.4%–19.7% decrease in GWP was observed (see Table 5). Results were less sensitive to reductions in other animal-based ingredients such as cheese, at least in meat-based recipes. However, when the amount of cheese in vegetarian recipes (e.g., vegetarian lasagne) was

Table 5
Sensitivity analysis showing how the GWP of meals change to a ± 20% change in an input or model parameter. WF = Whole-food.

Change in parameter	GWP original (kg CO_2-eq)	GWP after change (kg CO_2-eq)	Change in GWP (%)
Change the amount of most contributing ingredients in recipes			
Reduce amount of beef by 20% - Beef lasagne	5.78	4.80	17.0%
Reduce amount of beef by 20% - Beef chilli	4.97	3.99	19.7%
Reduce amount of chicken by 20% - Chicken teriyaki	0.78	0.66	15.4%
Reduce amount of chicken by 20% - Chicken curry	0.77	0.63	18.2%
Reduce amount of cheese by 20% - Beef lasagne	5.78	5.70	1.4%
Reduce amount of cheese by 20% - Vegetarian lasagne	0.92	0.83	9.8%
Change emission factors of most contributing ingredients			
Reduce emission factor of beef by 20% - Beef lasagne	5.78	4.81	16.8%
Reduce emission factor of beef by 20% - Beef chilli	4.97	3.99	19.7%
Reduce emission factor of chicken by 20% - Chicken teriyaki	0.78	0.67	14.1%
Reduce emission factor of chicken by 20% - Chicken curry	0.77	0.64	16.9%
Change total transport distance			
Increase transport distance by 20% - Beef lasagne	5.78	5.80	0.2%
Increase transport distance by 20% - Beef chilli	4.97	4.97	0.1%
Increase transport distance by 20% - Chicken teriyaki	0.78	0.78	0.8%
Increase transport distance by 20% - Chicken curry	0.77	0.77	0.3%
Increase transport distance by 20% - WF vegan lasagne	0.26	0.27	5.5%
Increase transport distance by 20% - WF vegan chilli	0.18	0.19	8.6%
Increase transport distance by 20% - WF vegan teriyaki	0.21	0.23	8.6%
Increase transport distance by 20% - WF vegan curry	0.11	0.12	6.6%

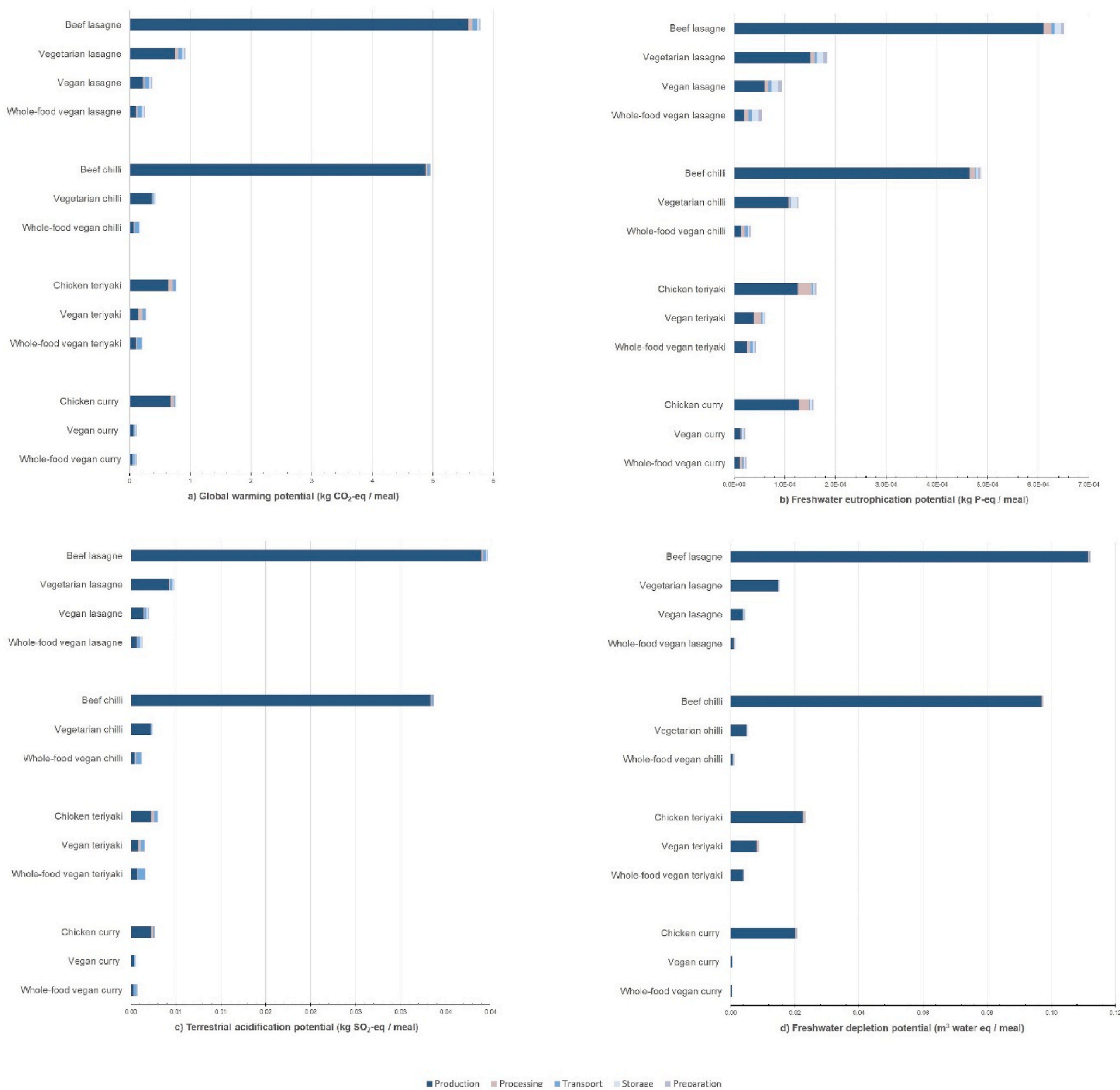

Fig. 2. The environmental impacts of meat-based, vegetarian, vegan and whole-food vegan lasagne, chilli, teriyaki and curry meals, and the contributions of different life cycle stages.

reduced by 20%, a 9.8% decrease in the overall GWP of the recipe was observed.

The results were also sensitive to changes in the emission factors of the most contributing ingredients. For example, when the emission factor of 1 kg beef was decreased by 20%, the GWP of the beef lasagne recipe changed by 16.8%, and the GWP of the beef chilli recipe changed by 19.7%. Similarly, when the emission factor of 1 kg chicken was decreased by 20%, the GWP of the chicken teriyaki and chicken curry changed by 14.1 and 16.9% respectively. Diet, feed composition, the use of N fertilisers, animal and manure management practices have been shown to influence the magnitude of GHG emissions of meat (Aan den Toorn et al., 2021; Hou et al., 2015), influencing the GWP of meat products and thus also the GWP of meat-based meals.

Conversely, results were not sensitive to changes in the amount of transportation of ingredients. A 20% increase in transport distance led to 0.1–0.8% increase in the GWP of meat-based meals. The results of the whole-food vegan meals were more sensitive to increases in transport distance, where a 20% increase in transport distance led to 5.5–8.6% increase in the GWP of whole-food vegan meals.

3.8. Summary of results and ranking of meals

The results of this study are summarised in a heat map (Fig. 8), where all the meals were ranked according to their environmental impacts (following Schmidt Rivera and Azapagic, 2019). Meals with the lowest impact are shaded in green, while meals with the highest impact are shaded in red in each impact category as well as across all impact categories (i.e. overall ranking). If all the impacts are weighted equally, the most environmentally sustainable meals are vegan meals, namely vegan and whole-food vegan curry, whole-food vegan chilli, whole-food vegan lasagne and whole-food vegan teriyaki. The least environmentally sustainable meals are beef lasagne, beef chilli and vegetarian lasagne followed by chicken teriyaki and chicken curry.

When looking at the different recipe variations of the same meals, the

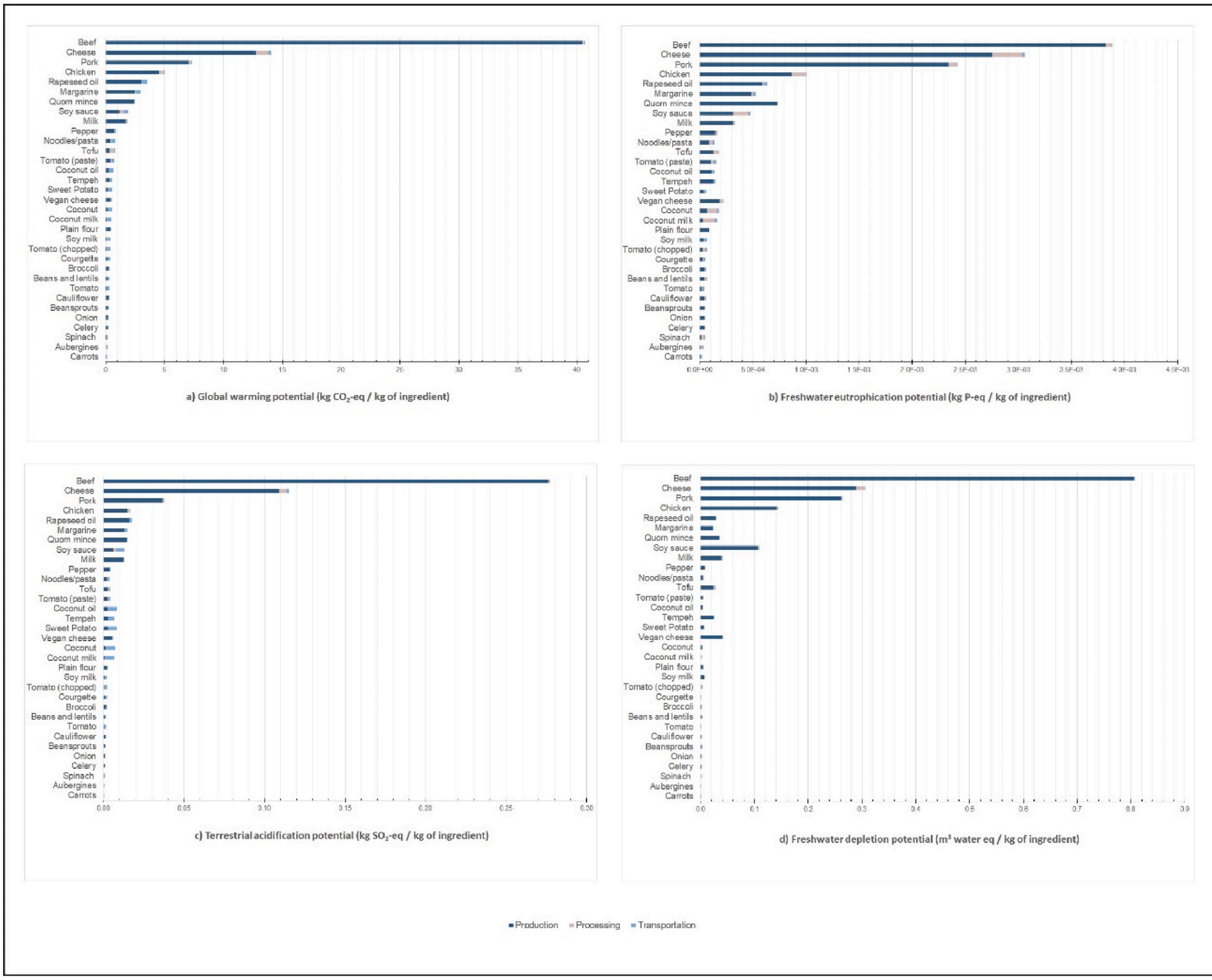

Fig. 3. GWP, FEP, TAP and WDP values of various ingredients expressed in kg of ready-to-use ingredient from farm to kitchen (i.e., production, processing and transportation stages).

results clearly show that the vegan versions of the meals are always the most environmentally sustainable (see Fig. 9). This study has not only demonstrated the benefits of LCA for identifying impact hotspots (Pelletier, 2015) but also has highlighted the importance of focusing on recipe ingredients as a first point of intervention to reduce the overall environmental impact of meals instead of focusing on where the ingredients come from and whether or not they are local. This study, along with others (e.g., Batlle-Bayer et al., 2020; Davis et al., 2010; Sturtewagen et al., 2016) demonstrated that substantial reductions in the environmental impacts of meals can be achieved by substituting ingredients in meals with plant-based alternatives and shifting towards plant-based recipes.

With an emphasis on ingredients, any meal can be turned into a 'plan(e)t-friendly' meal regardless of the cuisine or meal type. With creativity and knowledge about various plant-based ingredients, traditional meals that have high environmental impact can be turned into low-impact meals by replacing high-impact ingredients (e.g., beef, cheese, pork, chicken) with low-impact, plant-based alternatives (e.g., such as beans, lentils and vegetables) while still keeping the style and feel of the dish.

Considering that even if all non-food system GHG emissions were halted immediately, emissions from the food system alone could preclude achieving the 1.5° and 2 °C climate change targets (Clark et al., 2020), reducing emissions from the food system by shifting towards the consumption of plant-based meals, is a matter of urgency rather than an option. Shifting towards plant-based dietary patterns not only offers clear benefits for the environment but also offers significant co-benefits for human health (Jia et al., 2019) and also protects animals and their rights and interests, which are generally neglected and ignored in discussions on sustainable food systems and sustainable production and consumption patterns (Visseren-Hamakers, 2020).

3.9. Limitations and recommendations for future work

While LCA is a well-established and useful tool for assessing the environmental impacts of products and services, it has its own limitations (Toniolo et al., 2021). LCA studies depend on numerous assumptions about parameters and scenarios, which can affect the results. Some of the major limitations that can affect the results of this study are described below.

One of the most critical stages of any LCA is the LCI and successive life cycle inventory assessment. In this study, the inventory data for ingredients were sourced from the literature and data specific for the country of origin and for the production systems were chosen whenever available. However, in some cases no inventory data were available for a specific ingredient produced in a specific country and therefore data from a different country was used which may have different climate conditions and production methods in place. It is also important to keep in mind that this study was based in the UK and therefore model parameters (e.g., electricity emission factors, imports, transportation mode and distances) and results are specific to this geographical context.

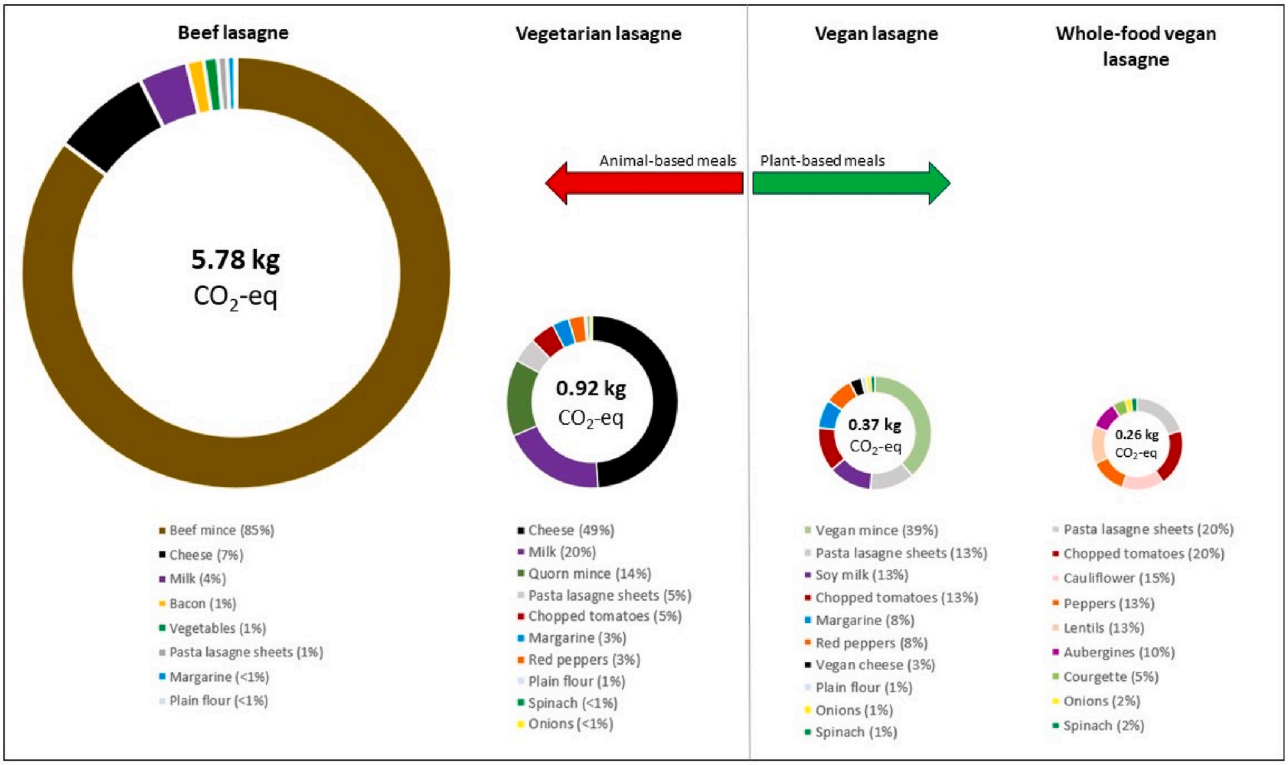

Fig. 4. The GWP of the different recipe variations of lasagne meals. Note: The areas of the circles represent the magnitudes of the GWP of each meal. Inside each circle, the contribution of ingredients used in each recipe to the overall GWP of the recipe can be seen.

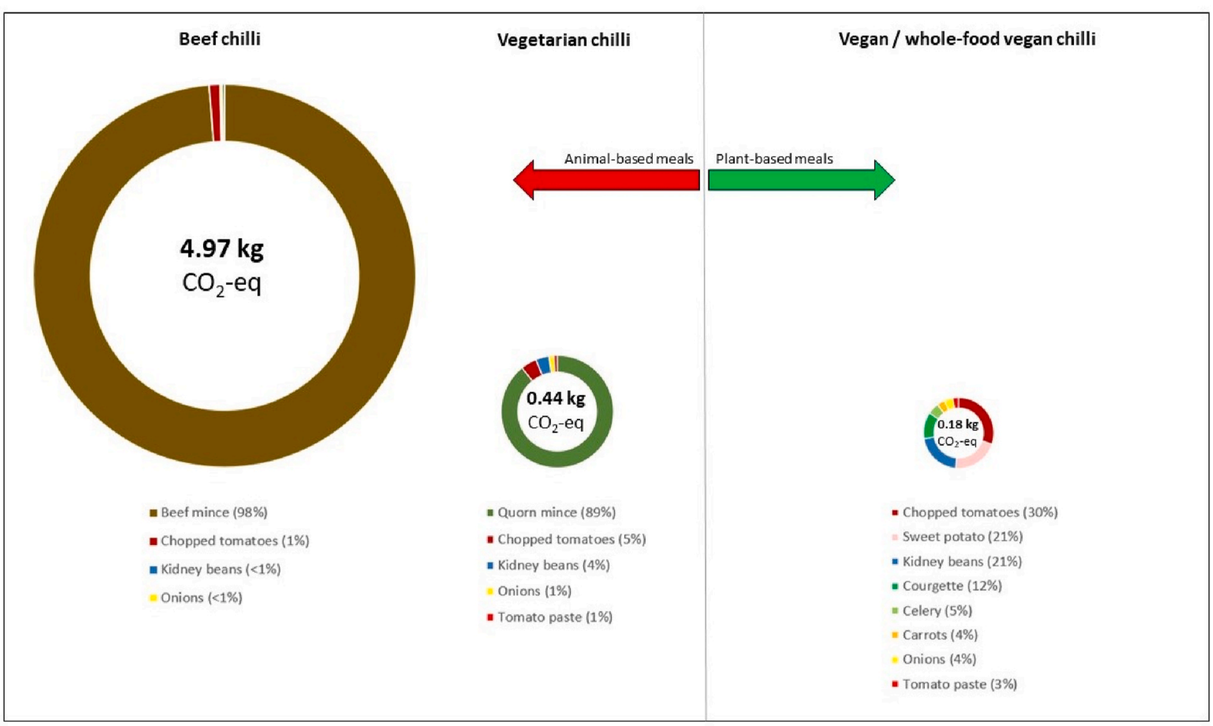

Fig. 5. The GWP of the different recipe variations of chilli meals. Note: The areas of the circles represent the magnitudes of the GWP of each meal. Inside each circle, the contribution of ingredients used in each recipe to the overall GWP of the recipe can be seen.

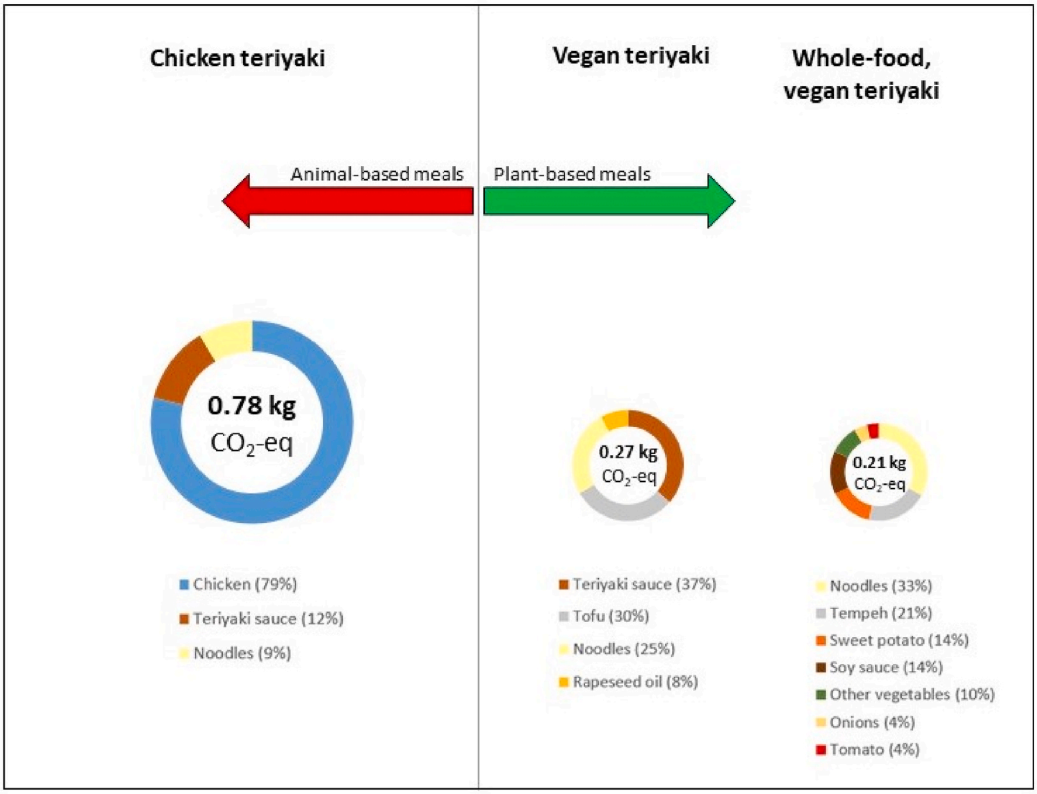

Fig. 6. The GWP of the different recipe variations of teriyaki meals. Note: The areas of the circles represent the magnitudes of the GWP of each meal. Inside each circle, the contribution of ingredients used in each recipe to the overall GWP of the recipe can be seen.

Fig. 7. The GWP of the different recipe variations of curry meals. Note: The areas of the circles represent the magnitudes of the GWP of each meal. Inside each circle, the contribution of ingredients used in each recipe to the overall GWP of the recipe can be seen.

	GWP	FEP	TAP	WDP		Total score		Overall ranking
Vegan curry	1	1	1	2		5		**1**
Wole-food vegan curry	2	2	2	1		7		**2**
Whole-food vegan chilli	3	3	3	3		12		**3**
Whole-food vegan lasagne	5	5	4	4		18		**4**
Wole-food vegan teriyaki	4	4	6	5		19		**5**
Vegan teriyaki	6	6	5	8		25		**6**
Vegan lasagne	7	7	7	6		27		**7**
Vegetarian chilli	8	8	8	7		31		**8**
Chicken curry	9	9	9	10		37		**9**
Chicken teriyaki	10	10	10	11		41		**10**
Vegetarian lasagne	11	11	11	9		42		**11**
Beef chilli	12	12	12	12		48		**12**
Beef lasagne	13	13	13	13		52		**13**

Fig. 8. Ranking of the meals based on their environmental impacts. Note: meals were ranked from 1 to 13 (1 was given to the meal with the lowest impact in a given impact category, 2 to the second lowest etc.), then scores were summed. The lower the total score, the lower the environmental impact of the meal and thus the more sustainable the meal is.

Methodological choices (e.g., system boundaries, functional unit, impact categories, indicators used, value choices) also affect the comprehensiveness of the study. This study was limited to four impact categories (see section 2.6). While they provide a good overview of the most important environmental impacts associated with food production and consumption, it would be useful to study other impacts that are also relevant to the food sector, such as land use change, biodiversity loss as well as human- and eco-toxicity to get a more comprehensive understanding of the environmental impact of meals.

Determining an appropriate functional unit for food and meals can be a challenge (Thoma et al., 2022). While the functional unit used in this study (i.e., one meal) provides a basis for comparison of the environmental impacts of different types of meals, other relevant functions such as the nutritional quality of ingredients and meals (Saarinen et al., 2017), are not taken into account by the chosen functional unit. Due to the complexities involved in assessing both the environmental and the nutritional impacts of meals using one method (e.g. LCA), it is often more suitable to evaluate the nutritional quality of meals separately using well-established and comprehensive nutritional analysis methods as opposed to using a simplified nutrition-based metric within the LCA (Ridoutt, 2021).

While evidence suggests that diets and meals made with minimally processed whole plant foods are health promoting (Crosby et al., 2008; McMacken and Shah, 2017; Morin et al., 2019), a limited number of studies examine the relationship between the environmental and nutritional impact of meals within LCA (Grigoriadis et al., 2021).

	GWP	FEP	TAP	WDP		Total score		Overall ranking
Wole-food vegan lasagne	1	1	1	1		4		**1**
Vegan lasagne	2	2	2	2		8		**2**
Vegetarian lasagne	3	3	3	3		12		**3**
Beef lasagne	4	4	4	4		16		**4**
Vegan / whole-food chilli	1	1	1	1		4		**1**
Vegetarian chilli	2	2	2	2		8		**2**
Beef chilli	3	3	3	3		12		**3**
Whole-food vegan teriyaki	1	1	2	1		5		**1**
Vegan teriyaki	2	2	1	2		7		**2**
Chicken teriyaki	3	3	3	3		12		**3**
Vegan curry	1	1	1	2		5		**1**
Whole-food vegan curry	2	1	2	1		6		**2**
Chicken curry	3	3	3	3		12		**3**

Fig. 9. Ranking of the recipe variations of the same meals based on their environmental impacts. Note: 1 was given to the recipe variation with the lowest impact in a given impact category, 2 to the second lowest etc.). The lower the total score, the lower the environmental impact of the recipe variation and thus the more sustainable the recipe is.

Consequently, a comprehensive nutritional assessment to better understand both the environmental impacts as well as the nutritional quality of meals will be completed in the next phase of this research. This will facilitate decision making and will provide insights into any potential trade-offs or tensions between the environmental and nutritional impacts of different types of meals and recipe variations.

4. Conclusions

This study estimated the environmental impacts of a range of meals from different cuisines (Italian, Asian and Indian) and their recipe variations (meat-based, vegetarian, vegan, and whole-food vegan). The results showed that it was not the type of cuisine that determined the environmental impact of meals, but the ingredients used in the recipes. Results clearly showed that the plant-based versions of meals (i.e., vegan and whole-food vegan meals) had substantially lower environmental impacts than their meat-based and vegetarian versions across all impact categories. On average, meat-based meals had 14 times higher environmental impact, while vegetarian meals had 3 times higher environmental impact than vegan meals. Of all the meals, whole-food vegan meals, i.e., meals made with whole, minimally processed plant-based ingredients, had the lowest environmental impact.

The findings of this study suggest that substantial reductions in the environmental impacts of meals can be achieved when ingredients that have high environmental impact (i.e., animal-based ingredients such as beef, cheese, pork or chicken) are removed and replaced in recipes with ingredients that have lower impact (i.e., vegan meat substitutes, tofu, tempeh). However, the greatest reductions can be achieved when animal-based ingredients are replaced with whole or minimally processed plant-based ingredients (i.e., unprocessed vegetables, legumes etc.) in recipes.

The agricultural and ingredient production stage was a hotspot and the single biggest contributor to the environmental impacts of meals. Other life cycle stages such as transportation, processing and preparation had relatively small contributions. This highlights the importance of focusing on what the ingredients are in the meals and not necessarily where these ingredients come from. Since the impacts of animal-based ingredients can markedly exceed those of plant-based ingredients, shifting away from meals made with animal products is a far more effective strategy to lower the environmental impact of meals than simply sourcing ingredients locally. This study demonstrates that moving away from meals centred around meat, dairy and other animal products to meals made with plant-based ingredients offers clear environmental benefits and plays an important role in mitigating climate change and safeguarding environmental sustainability.

CRediT authorship contribution statement

Berill Takacs: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Julia A. Stegemann:** Conceptualization, Validation, Writing – review & editing, Supervision. **Anastasia Z. Kalea:** Conceptualization, Validation, Writing – review & editing, Supervision. **Aiduan Borrion:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134782.

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