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CARBON FOOTPRINTING

The carbon footprint of common vegetarian and non-vegetarian meals in Portugal: an estimate, comparison, and analysis

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Abstract

Purpose Vegetarian diets have been suggested as one way to reduce the carbon footprint of individuals, when compared to standard Western diets, given the latter's inclusion of high-carbon footprint animal foods. However, it is unclear if, within usually consumed meals, the average vegetarian meals have a significantly lower carbon footprint than non-vegetarian meals. Often consumed meals were designated as "common" in this research and obtained from real consumers' food diaries. The purpose of this research is to find out if, in Portugal, common vegetarian meals have a lower carbon footprint than common non-vegetarian meals; and, to communicate the results in a format that might lead consumers in Portugal to reduce this food carbon footprint of theirs.

Methods We conducted a novel analysis for Portugal, namely due to three factors: (1) its focus on meals, rather than ingredients; (2) the inclusion of national food consumption, rather than food production; and (3) presenting the results in a traffic light system. It was also tested how non-vegetarian meals' carbon footprint would change if animal protein was replaced by plant protein.

Results The carbon footprint of common non-vegetarian meals in Portugal is 5.5 times higher than that of common vegetarian meals in Portugal. There is a wide range of carbon footprint values for vegetarian meals in Portugal, specifically, the 5th percentile is 8.5 times smaller than the 95th percentile. Moreover, the common non-vegetarian meals in Portugal when "made" vegetarian have a carbon footprint about 6.4 times lower than the common non-vegetarian meals in Portugal.

Conclusions There are known limitations in this research, besides the unknown ones, such as using only one environmental impact indicator, namely the carbon footprint (rather than the ecological footprint, other, or even none of these); the limited breadth of studies selected, to obtain the food items' carbon footprint (reviews, meta-studies, and local studies); and the narrow LCA boundaries and characteristics included in those and subsequent analysis (of the food items' bioavailability and nutritional functional unit, among others). However, within the scope of this research, the three general hypotheses of this research have been confirmed. It can be concluded that vegetarian food is a potential solution for food's environmental sustainability in Portugal.

Keywords Sustainable diets · Plant-based diets · Carbon footprint · Food consumption · Sustainability

1 Introduction

1.1 The environmental impact of food: the global scenario

To frame the purpose of this research, before delving into why it focuses on Portugal's food carbon footprint, we look into the environmental impact of food globally and present it here briefly. Food is one of the anthropogenic influences that contribute to climate change, notably because greenhouse gasses (GHG) are emitted by the global food system (IPCC 2014, 2018), from food production to food consumption. Besides the emission of GHG, food systems have other environmental impacts, such as loss of natural ecosystems and loss of biodiversity (IPCC 2019). For example, agriculture and forestry are responsible for requiring about 70% of the planet's freshwater consumption (IPCC 2019), requiring about 50% of all habitable land (IPCC 2019), and causing eutrophication (IPCC 2019). Agriculture and forestry also contribute to climate change, which in turn increases global temperatures (IPCC 2019), causing extreme weather events such as heat waves, droughts, rainfall, and storms that in turn degrade soils, cause flooding, and endanger animals and

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plants, among others (IPCC 2019). In addition to environmental impact, climate change has an economic and social impact on agriculture and forestry as it disrupts the food system itself and human livelihoods, namely agricultural crops and pests, among others (IPCC 2019).

From the various environmental impact indicators, we looked to use the one most understood and adopted by the general public, while simultaneously being accepted and used in scientific studies with a similar theme and objectives to this research. Within the various environmental indicators, where indices (aggregators) and benchmarks, among others are included (Hák et al 2007), their major commonality is that "there is no ideal indicator that fully encompasses all the desired qualities" (Hák et al. 2007, p. 2).

The carbon footprint was chosen, despite its limitations, such as its application to food and diets. Namely, the disparate results when different GHG are included, different inputs and scopes in the same calculations, among others (Pandey et al. 2011). Moreover, there are implicit limitations in using a sole indicator.

The carbon footprint is generally defined as the amount of GHG emitted into the atmosphere, expressed in terms of carbon dioxide equivalents (CO_2eq), relating to certain products, individuals, and/or within a specific limit (IPCC 2014; Pandey et al. 2011; Wiedmann and Minx 2008).

Food is estimated to account for between 21 and 37% of all GHG emissions worldwide (IPCC 2019). To break down which foods are the biggest contributors, we use Poore and Nemecek's (2018) estimate that food contributes to 26% of all GHG emissions, out of which animal foods have a bigger carbon footprint than plant-based foods (Poore and Nemecek 2018; Clune et al. 2017), and within that 26%, at least 53% are related to animal production (31% of livestock production and aquaculture, 6% of harvests for animal feed, and 16% of land use for livestock) (Poore and Nemecek 2018; Ritchie and Roser 2020). Of the remaining 47%, 29% of food-related GHG emissions derive from plant-based food production (21% for human consumption and 8% for land use) and 18% result from the supply chain of all foods (6% transport, 5% packaging, 4% processing, 3% in retail) (Poore and Nemecek 2018; Ritchie and Roser 2020). Bovine meat (beef, calf, among others) is the food type with the highest carbon footprint, both per kilogram and per 100 g of protein (Poore and Nemecek 2018; Clune et al. 2017), mostly due to enteric fermentation (Poore and Nemecek 2018; Clune et al. 2017). The foods with the lowest carbon footprint are certain nuts, fruits, and vegetables (Poore and Nemecek 2018; Clune et al. 2017).

The mitigation of food's environmental impacts can be done through diets with few animal products, rich in vegetables, legumes, fruit, nuts, seeds, and whole grains, with a limit of carbohydrates, among others, such as food waste (IPCC 2019). In particular, by replacing animal-based food with plant-based food (especially, legumes and nuts) and by replacing red meat with more efficient protein sources (IPCC 2019).

Several studies, which have focused on the adoption of different types of diets and their environmental impact, suggest that high consumption of animal foods has a bigger environmental impact than the consumption of plant-based foods (Carlsson-Kanyama and González 2009; Clune et al. 2017; Esteve-Llorens et al. 2020; González et al. 2011; Poore and Nemecek 2018; Scarborough et al. 2014; Stehfest et al. 2009; Tilman and Clark 2014; Wilson et al. 2013).

Most studies on the carbon footprint of food, including in Portugal, focus on the carbon footprint of different food types/ingredients (Boer et al. 2011; Nijdam et al. 2012; Reijnders and Soret 2003) and/or different diets (Aleksandrowicz et al. 2016; Baroni et al. 2007; Carlsson-Kanyama 1998; Esteve-Llorens et al. 2020; Poore and Nemecek 2018; Scarborough et al. 2014; Springmannet al. 2016; Tilman and Clark 2014). The data used in these studies, to analyze food types or diets, range from macro, such as national food scales (Scarborough et al. 2014), to micro, such as measuring food emissions on the ground (Morais et al. 2018a, b) and food diaries of individuals (Lopes et al. 2018). They also include other data such as surveys on agricultural producers (Morais et al. 2018b) and individual surveys on their food and eating habits (Scarborough et al. 2014).

1.2 The environmental impact of food: the scenario in Portugal

In Portugal, the traditional Portuguese diet and the Mediterranean diet, which are both considered to be more sustainable than the globalized Western diet (Esteve-Llorens et al. 2020; Johnston et al. 2014), are not representative of contemporary diets in Portugal (Esteve-Llorens et al. 2020; Galli et al. 2020; Lopes et al. 2018). The current food scenario in Portugal is like other industrialized countries and follows global trends.

About 30% of the ecological footprint (EF) (Galli et al. 2020; Lin et al. 2018) per capita in Portugal derives from food production and consumption. Portugal is the Mediterranean country with the largest ecological food footprint per capita (1.5 global hectares) (Galli et al. 2017). The EF from food production in Portugal is less than half (less than 0.6 global hectares) compared to the EF from food consumption (what is produced plus imported, totaling the country's consumption), similar to the median of other Mediterranean countries (Galli et al. 2017). Portugal's carbon footprint per capita per day is 4.20 kg CO_2eq, in line with countries such as Spain (4.39 kg CO_2eq) and France (4.11 kg CO_2eq), among others (Esteve-Llorens et al. 2020), in which livestock and cereal products represent about 65% of total GHG emissions (Esteve-Llorens et al. 2020).

In Portugal, to mitigate the aforementioned environmental impact of food, in the realm of food consumption, the Portuguese Nutrition Association (Associação Portuguesa de Nutrição, APN), with the institutional support of the Directorate-General of Health (APN 2017), created a guide for sustainable food (APN 2017), which takes into account the type of food, the mode of food production, seasonality, and short distribution chains. Globally, to mitigate the environmental impact of food, the type of food is more relevant than where it was produced and consumed (Poore and Nemecek 2018). APN's recommendations for a sustainable and healthy diet is also in the type of food, recommending that 3/4 of the main meal should be plant-based foods and that 1/4 should be animal-based foods or legumes while limiting the consumption of red and processed meats (APN 2017).

1.3 The carbon footprint of food in Portugal

In Portugal, the carbon footprint of food is similar to the global scenario. The carbon footprint of agriculture contributes to at least 11% of the country's carbon footprint, excluding land use for agriculture (EPA 2020), which makes this number higher than reported. Emissions from cattle, sheep, and poultry production continue to increase in recent years (APA 2020). Compared to other European countries, Portugal is the European Union's country with the highest carbon footprint for food consumption (Sandström et al. 2018), and the same is the case for its ecological footprint (Galli et al. 2020). The main cause is the high consumption of meat (about 200 g per day per capita)[1] (Esteve-Llorens et al. 2020) and fish (Galli et al. 2020), depending on which environmental indicator and studies are considered. Overall, animal-based food is the biggest contributor to the carbon footprint of food (Esteve-Llorens et al. 2020), and most animal-based foods have a bigger carbon footprint than plant-based foods.

Food products considered traditionally Portuguese and locally produced, such as rice (Portuguese Republic 2019), milk from the region of Azores (Morais et al. 2018b), and beef (Morais et al. 2018a), have a lower carbon footprint than the same imported products (Poore and Nemecek 2018; Clune et al. 2017). Foods produced according to non-intensive production practices (organic or extensive) also have a lower carbon footprint than those produced in intensive mode (Eyhorn et al. 2019; Morais et al. 2018a, b). Nevertheless, these types of products represent only a small fraction of Portugal's food production and consumption (Cabo et al. 2016; APA 2019).

[1] Not only is the carbon footprint of the food consumed high, but the amount consumed is excessive. This is the case both in Portugal and in other European countries (Esteve-Llorens et al. 2020).

With this scenario, the main research question that came up was: is vegetarian food a potential solution for food's environmental sustainability in Portugal?

The following hypotheses were established:

Hypothesis 1: In Portugal, common vegetarian meals have, on average, a lower carbon footprint than common non-vegetarian meals.
Hypothesis 2: There is a wide range of carbon footprint values for vegetarian meals in Portugal.
Hypothesis 3: There are conventional non-vegetarian meals in Portugal that, adapted to be vegetarian meals, can considerably reduce their carbon footprint.

2 Methods

Two objectives were established for this research:

1. To find out if, in Portugal, common vegetarian meals have a lower carbon footprint than common non-vegetarian meals.
2. Present the results in an immediate, comparable, relevant, and appealing format that might lead Portuguese consumers to reduce their food carbon footprint.

To achieve the first objective, the carbon footprint of certain foods was estimated, mostly from global meta-studies (Clune et al. 2017; Poore and Nemecek 2018), since food in Portugal follows global trends (Esteve-Llorens et al. 2020; Lopes et al. 2018).

The datasets of these meta-studies encompass, among other factors, the ingredient or "simple food item" (McLaren et al. 2021) (for example, apples), its median and mean carbon emission (kg CO_2eq), and the study, or studies, used to reach that carbon emissions value. These values are not specific to Portugal, despite being possible to reach more accurate, and Portugal-specific, values of these foods' carbon emissions, as well as further ensuring the consistency of the LCAs (McLaren et al. 2021) that are being compared.

However, these values were adapted to Portugal's reality, detailed below (1). Namely, taking into account the degree of supply of the internal market (how much Portugal consumes, from what it produces and how much it imports) and using a Portugal-specific food item carbon footprint for whenever those were available within the referenced studies. When certain foods' footprints were not available from these two meta-studies (Clune et al. 2017; Poore and Nemecek 2018), other studies were used. Namely for foods "associated" with Portugal (such as rice, beef, and milk from the Azores) and foods consumed in Portugal with relevance within the category of vegetarian food (such as seitan). For all foods, it was estimated how much is produced and consumed in Portugal, using the “Degree of supply of the internal market,” to adapt the values used of the global and local carbon footprint.

To ensure consistency in the use of these studies, and relevance in the quantitative estimation of the carbon footprint of meals and foods, the LCA components were reviewed (Online Resources Annexes B and C), and the results were adjusted according to the food items’ estimated “Degree of supply of the internal market” (1 and “DSIM” in Online Resources Annex A). That is, for studies that did not include certain phases of the life cycle of a food or product, the GHG emissions values of these phases were added, taken from the baseline meta-study by Poore and Nemecek (2018). In the LCA of this meta-study, the authors include from pre-production (the inputs, such as fertilizer and feed) to the transport to retail phase, but exclude the phases after this (e.g., waste/loss at retail and preparation, among other actions, by the consumer). For example, by estimating the carbon footprint of a liter of milk in Portugal, and using two values of milk’s carbon footprint, at the global level (3.2 kg CO2eq) (Poore and Nemecek 2018) and at the national level (0.8 kg CO_2eq) (Morais et al. 2018b), we added to the latter the LCA phases present in the study at the global level: processing (0.1 kg CO_2eq), packaging (0.1 kg CO_2eq), and retail (1.3 kg CO_2eq) post-farm.

To validate these results, FAO’s (2019) quantitative data on GHG emissions from agriculture was used. These data are not directly comparable with the studies used in this research, as they are estimates only within the “farm gate” (i.e., only within the farm/site where they were produced, without the other components of the value chain included), nor is it possible to estimate the accuracy of the data, as they are provided by each member country (FAO 2019).

Thus, the carbon footprint of food (*CF*) (kg CO_2eq) was estimated by calculating (1):

$$\left(Global\ meta-study\ CF + LCA\ correction\ of\ postfarm\ global\ meta-study\right) * \left(1 - Degree\ of\ supply\ of\ the\ internal\ market\ (\%)\right) + \left(Local\ study\ CF + LCA\ correction\ of\ local\ postfarm\ study\right) * Degree\ of\ supply\ of\ the\ internal\ market\ (\%) \quad (1)$$

As an example (1), for 1 kg of cheese, in which: *Global meta-study CF* = 23.9 kg CO_2eq; *LCA correction of postfarm global meta-study* = 0 (does not apply); – *Degree of supply of the internal market* = 57.65%; *Local study CF* = 9.1 kg CO_2eq; *LCA correction of local postfarm study* = 1.2 kg CO_2eq (0.8 processing + 0.2 packaging + 0.3 retail), is:

$$(23.9 + 0) * (1 - 0.5765) + (9.1 + 1.2) * 0.5765$$

This results in a carbon footprint (*CF*) of 16.1 kg CO_2eq/kg of cheese.

To best ensure relevance, accuracy, and consistency in the results, the functional unit was considered, like in Poore and Nemecek’s (2018), presenting the carbon footprint not only per kilogram/liter of food but also per 100 g of protein, for food items which main nutritional function is to provide protein, such as meat, fish, and legumes.

In addition to estimating the carbon footprint of food, the carbon footprint of common meals in Portugal was also estimated, to achieve the first objective. For this, we used real consumers’ food diaries’ data from the National Food and Physical Activity Survey (IAN-AF, in its original nomination) of 2015–2016 (Lopes et al. 2017, p. 21). The data provided was a random sample of 1904 “recipes” (IAN-AF 2015–2016’s nomination), i.e., meal and full meal components (not food diaries per individual). Within each of the categories (“meat,” “fish,” and “vegetarian”), a subcategory was estimated according to the frequency of these recipes in its category. For example, “roast pork loin,” “roast pork ribs,” and “roasted piglet” were included in the subcategory created by the authors of “roasted pork.”

We also used online cooking recipes to estimate the ingredients and quantities that make up the selected IAN-AF meals. The number of ingredients in the recipes was then estimated. Finally, to standardize meals to include at least two out of three elements—protein, carbohydrates, and vegetables—a “side (estimated)” was added when the carbohydrate component was not present in the meal, in a similar amount to other recipes, or as suggested in the recipe itself (but not quantified), of 100 g of potatoes or 100 g of rice. A quantitative analysis of the meals was then calculated, vegetarian meals compared to non-vegetarian, to test the previously proposed hypotheses:

Hypothesis 1: In Portugal, common vegetarian meals have, on average, a lower carbon footprint than common non-vegetarian meals.
Hypothesis 2: There is a wide range of carbon footprint values for vegetarian meals in Portugal.
Hypothesis 3: There are conventional non-vegetarian meals in Portugal that, adapted to be vegetarian meals, can considerably reduce their carbon footprint.

To achieve the second objective, all these results were presented, when relevant, in a traffic light system (Panzone et al. 2020). That is, food and meals were categorized in red, yellow, and green colors, representing a high, medium, or low carbon footprint, respectively. We did not find in the literature a definitive logic to define the range of the three traffic light system colors, including for carbon footprint (kg CO_2eq/kg). Thus, we assessed it according to the results’ average, median, and number of results.

This is immediate (noticeable) and comparable (compares foods with foods and meals with meals), appealing (color system rather than a numerical carbon footprint ranking) and relevant (presenting not only foods but also meals that are actually eaten in Portugal). It is also directed to the action of individuals since they see conventional meals framed against vegetarian meals. This can be used and tested in further research, in environments where consumers are able to choose from a food menu, influencing their food choices, in restaurants and public canteens [retail and services (end point logistics), as described in McLaren et al. (2021)].

Still within this second objective, and contributing to framing vegetarian meals, the meals' carbon footprint variation was estimated to replace the animal protein with a plant-based protein, maintaining the same protein ratio (Poore and Nemecek 2018).

3 Results

3.1 The carbon footprint of food ingredients in Portugal

When calculating the carbon footprint of foods/ingredients consumed in Portugal (Table 1 and Online Resource Annex A), the values are in line with similar global studies (Clune et al. 2017; Poore and Nemecek 2019) and national studies (Esteve-Llorens et al. 2020).

Ingredients of animal origin have the highest carbon footprint, with beef in the first place, with 79.5 kg of CO_2eq emitted per kilogram. Mutton comes next, with almost half the emissions of beef, at 41.0 kg of CO_2eq per kilogram. In third place are crustaceans, such as shrimp, prawns, and mussels, among others, with almost half of the emissions of mutton, with 21.1 kg of CO_2eq per kilogram. The top eight are of animal origin: cheese (16.1 kg CO_2eq/kg); octopus and similar (other cephalopods, such as squid and cuttlefish) (12.5 kg CO_2eq/kg); fish (10.2 kg CO_2eq/kg), which includes various fish such as hake and salmon; pork (9.1 kg CO_2eq/kg); and butter (8.7 kg CO_2eq/kg).

The plant-based ingredients with the highest carbon footprint per kilogram, after animal-based foods, are oils: palm oil (7.3 kg CO_2eq/kg), sunflower oil (6.3 kg CO_2eq/kg), olive oil (3.8 kg CO_2eq/kg), and sesame oil (3.6 kg CO_2eq/kg).

Of the plant-based ingredients above 3 kg CO_2eq/kg is cane sugar (3.2 kg CO_2eq/kg) and tofu (3.2 kg CO_2eq/kg). These are on par with eggs (3.4 kg CO_2eq/kg) and mackerel (2.8 kg CO_2eq/kg), the latter being the animal-based ingredient with the smallest carbon footprint, followed by tuna (4.2 kg CO_2eq/kg) and cod (4.3 kg CO_2eq/kg) and are half the value of poultry (6.3 kg CO_2eq/kg).

Table 1 Greenhouse gas (GHG) emissions (kg CO_2eq/kg) per ingredient in Portugal

Category	Ingredient	kg CO_2eq/kg
Proteins	Beef	79.5
	Mutton	41.0
	Crustaceans	21.1
	Cheese	16.1
	Fish	10.2
	Octopus and similar	12.5
	Pork	9.1
	Poultry	6.3
	Codfish	4.3
	Tuna	4.2
	Eggs	3.4
	Tofu	3.2
	Mackerel	2.8
	Peanuts	1.4
	Other legumes	1.4
	Lentils	1.3
	Beans	1.0
	Soybeans	1.0
	Peas	0.9
	Chickpeas	0.7
	Seitan	0.6
	Walnuts/almonds/cashews	0.4
Milks	Dairy milk	1.4
	Soy milk	1.0
Dairy	Butter	8.7
	Yoghurt	1.9
Starches	Rice	3.0
	Wheat	1.6
	Corn	1.4
	Oats	1.0
	Potatoes	0.4
Oils	Palm oil	7.3
	Sunflower oil	6.3
	Olive oil	3.8
	Sesame oil	3.6
Vegetables	Cabbages	2.1
	Tomatoes	1.8
	Onions and garlic	0.4
	Carrots and other root vegetables	0.4
Fruit	Berries and grapes	2.9
	Avocado	1.1
	Bananas	0.9
	Apples	0.4
	Citrus	0.4
Sugar	Cane sugar	3.2
	Beet sugar	1.8

The animal-based ingredients with the lowest carbon footprint are yoghurt (1.9 kg CO_2eq/kg) and dairy milk (1.4 kg CO_2eq/kg). These values are on par with the highest carbon footprint plant-based ingredients, such as berries and grapes (2.9 kg CO_2eq/kg), kale (2.1 kg CO_2eq/kg), and tomatoes (1.8 kg CO_2eq/kg).

These results are also presented in a traffic light system (Panzone et al. 2020) (Table 2). The average carbon footprint of these foods is 6.1 kg CO_2eq/kg and the median is 1.9 kg CO_2eq/kg. The carbon footprint was considered high (red) when equal or above 8.0 kg CO_2eq/kg. It was considered medium (in yellow) when below 8.0 kg CO2eq/kg and above or equal to 1.9 kg CO_2eq/kg (the median being 1.9 kg CO_2eq/kg). And it was considered low (green) when below 1.9 kg CO_2eq/kg.

All ingredients with a high carbon footprint, red in the traffic light system, are of animal origin. Of the ingredients with a medium carbon footprint, yellow on the traffic light system, most are of plant origin. The oils are at the level of poultry, cod, and tuna (between 7.3 and 3.6 kg of CO_2eq/kg), being eggs, mackerel, and yoghurt the foods of animal origin with the lowest carbon footprint, within the yellow range. Of the foods of animal origin, only dairy milk presents a low carbon footprint, green in the traffic light system, with all other foods being of plant origin.

It is crucial, in line with other relevant studies, to also calculate and analyze the carbon footprint of food by its main role in diets, and to measure it by its primary nutritional benefit unit, namely per 100 g of protein (Table 3 and Online Resource Annex D).

In the traffic light system, with the average carbon footprint of these foods (Table 3) being 5.5 kg CO_2eq/kg, and the median being 1.9 kg CO_2eq/kg, the carbon footprint was considered high (in red) when equal to or above 4.0 kg CO_2eq/kg; medium (in yellow) when below 4.0 kg CO_2eq/kg; and above or equal to 1.0 kg CO2eq/kg and low (in green) when below 1.0 kg CO_2eq/kg.

Per 100 g of protein, animal ingredients all have a higher carbon footprint than plant ingredients, except for tofu, which has a medium (yellow) carbon footprint. All ingredients with a high (red) carbon footprint are of animal origin. With a medium carbon footprint (yellow), the only food of plant origin is tofu, the others being of animal origin (poultry, eggs, cod, tuna, and mackerel). All the ingredients with a low carbon footprint are plant-based.

3.2 The carbon footprint of common meals in Portugal

Using the estimated carbon footprint per kilogram of food (Online Resource Annex A), we calculated the estimated

Table 2 Traffic light system classification of GHG emissions (kg CO_2eq/kg) per ingredient in Portugal

Ingredient	Traffic light system classification
Beef	(red)
Mutton	(red)
Crustaceans	(red)
Cheese	(red)
Octopus and similar	(red)
Fish	(red)
Pork	(red)
Butter	(red)
Palm oil	(yellow)
Poultry	(yellow)
Sunflower oil	(yellow)
Codfish	(yellow)
Tuna	(yellow)
Olive oil	(yellow)
Sesame oil	(yellow)
Eggs	(yellow)
Tofu	(yellow)
Cane sugar	(yellow)
Rice	(yellow)
Berries and grapes	(yellow)
Mackerel	(yellow)
Cabbages	(yellow)
Yoghurt	(yellow)
Tomatoes	(green)
Beet sugar	(green)
Wheat	(green)
Peanuts	(green)
Legumes	(green)
Dairy milk	(green)
Corn	(green)
Lentils	(green)
Avocado	(green)
Beans	(green)
Soybeans	(green)
Soy milk	(green)
Oats	(green)
Peas	(green)
Bananas	(green)
Chickpeas	(green)
Seitan	(green)
Walnuts/almonds/cashews	(green)
Potatoes	(green)
Onions and garlic	(green)
Carrots and other root vegetables	(green)
Apples	(green)
Citrus	(green)

Table 3 Traffic light system classification of GHG emissions per 100 g of protein (kg CO_2eq/100 g of protein) per ingredient in Portugal

Ingredient	*Nutritional Functional Unit (NFU) Values*	Kg CO_2eq/100g protein	Traffic light system classification
Beef	*2.0*	39.9	
Mutton	*2.0*	20.6	
Crustaceans	*1.5*	14.2	
Cheese	*2.2*	7.4	
Pork	*1.6*	5.6	
Octopus and similar	*2.3*	5.5	
Fish	*2.3*	4.5	
Poultry	*1.7*	3.6	
Eggs	*1.1*	3.3	
Tofu	*1.6*	2	
Codfish	*2.3*	1.9	
Tuna	*2.3*	1.9	
Mackerel	*2.3*	1.2	
Legumes	*2.1*	0.6	
Lentils	*2.1*	0.6	
Peanuts	*2.6*	0.5	
Beans	*2.1*	0.5	
Soybeans	*2.1*	0.5	
Peas	*2.2*	0.4	
Chickpeas	*2.1*	0.3	
Walnuts/almonds/cashews	*1.6*	0.2	

carbon footprint of common meals in Portugal ("common" because they are real and the most consumed based on the food diaries from IAN-AF, mentioned earlier) and classified under a traffic light system (Table 4).

From a total of 92 recipes, where 33 were from the "meat" category, 32 from the "fish" category and 24 from the "vegetarian" category, resulted in an average carbon footprint of 3.0 kg CO_2eq and a median of 2.0 kg CO_2eq. The average carbon footprint of "meat" recipes is 4.8 kg CO_2eq, "fish" is 2.9 kg CO_2eq, and "vegetarian" is 0.7 kg CO_2eq. The average carbon footprint of "meat" and "fish" recipes is 5.5 times higher than "vegetarian" recipes (3.9 kg CO_2eq and 0.7 kg CO_2eq, respectively), proving hypothesis 1 ("Vegetarian meals have, on average, a smaller carbon footprint than the other usual meals in Portugal").

The meals' carbon footprint calculation was the sum of the 2 to 4 recipes' ingredients with the highest carbon footprint that compose the recipe. As an example, the carbon footprint of an "octopus" meal, with the recipe "roasted octopus" (carbon footprint 3.94 kg CO_2eq), which includes a slice of cornbread, was the sum of the carbon footprint of the following ingredients: 300 g of "octopus and similar" (3.74 kg CO_2eq), plus 25 g of "olive oil" (0.1 kg CO_2eq), plus 50 g of "corn" (0.07 kg CO_2eq), plus 100 g of "onions and garlic" (0.04 kg CO_2eq).

Within vegetarian meals, the median is 0.8 kg CO_2eq, the 5th percentile is 0.2 kg CO_2eq, the 95th percentile is 1.7 kg CO_2eq, and the standard deviation is 0.36 kg CO_2eq. The 5th percentile is 8.5 times smaller than the 95th percentile, proving hypothesis 2 of this research, that "There is a wide range of the carbon footprint within vegetarian meals in Portugal."

In the traffic light system, 32 recipes were classified as having a high carbon footprint (in red), when equal to or above 2.5 kg CO_2eq; 35 recipes were classified with a medium carbon footprint (in yellow), when below 2.5 kg CO_2eq and equal to or above 1.0 kg CO_2eq; and f25 recipes were classified with a low carbon footprint (in green), when below 1.0 kg CO_2eq.

All recipes with a high (red) carbon footprint are from the "meat" or "fish" categories. 46.9% of the recipes with the highest carbon footprint are "meat" and 53.1% are "fish." The average carbon footprint of the "meat" recipes with a red carbon footprint is 8.7 kg CO_2eq (per individual serving/person) and a median 4.7 kg CO_2eq. The average carbon footprint of the "fish" recipes with a red carbon footprint is 4.2 kg CO_2eq and a median of 3.7 kg CO_2eq.

Table 4 Traffic light system classification of GHG emissions (kg CO_2eq) by recipe in Portugal

Type	Sub-category	Recipe	kg CO_2eq	Traffic light system classification
Meat	Fried beef	Beef steak	20.0	
Meat	Baked/stewed beef	Stewed rib	15.9	
Meat	Fried beef	Veal steak	15.9	
Meat	Baked/stewed beef	Veal *jardineira* (mix)	12.8	
Meat	Pasta with meat	Pasta with minced meat	10.0	
Meat	Baked/stewed beef	Stewed beef	9.3	
Meat	Goat/lamb	Stewed goat	8.7	
Fish	Prawns	Seafood *cataplana*	8.6	
Meat	Lamb/sheep	Grilled lamb steak	8.6	
Meat	Burger	Beef burger	8.5	
Fish	Octopus	Baked octopus	6.5	
Fish	Fish rice	Seafood rice	5.7	
Fish	Octopus	Octopus rice	5.7	
Fish	Quiche	Seafood quiche	4.7	
Fish	Clams/mussels	Cooked mussels	4.6	
Meat	Grilled pork	Grilled pork chop	4.5	
Fish	Squid/cuttlefish	Grilled squid	4.5	
Fish	Clams/mussels	Cooked clam	4.5	
Fish	Octopus	Roasted octopus	3.9	
Meat	Baked/roasted turkey	Roast turkey	3.7	
Meat	Sausages	*Alheira*	3.4	
Fish	Roasted fish	Roasted sole	3.4	
Fish	Fried fish	Fried snapper	3.3	
Meat	Fried pork	*Rojões*	3.2	
Meat	Rice with meat	Duck rice	3.0	
Fish	Roasted fish	Roasted hake	2.8	
Meat	Roast pork	Roast pork ribs	2.8	
Fish	Codfish	Baked codfish	2.8	
Fish	Fried fish	Fried ray	2.7	
Fish	Squid/cuttlefish	Calamari	2.7	
Fish	Baked/stewed fish	Fish stew	2.6	
Fish	Squid/cuttlefish	Cuttlefish *feijoada*	2.5	
Fish	Codfish	Fried codfish	2.4	
Fish	Baked/stewed fish	Stewed hake	2.4	
Fish	Codfish	Codfish in the oven	2.4	
Fish	Fish pasta	Pasta with shrimp	2.4	
Fish	Salmon	Grilled salmon	2.3	
Meat	Roast pork	Roasted piglet	2.3	
Meat	Roast chicken	Oven-roasted chicken	2.2	
Fish	Fish pasta	Fish pie	2.2	
Fish	Fried fish	Breaded fish fillets	2.1	
Meat	Cooked/stewed chicken	Stewed chicken with carrots and peas	2.0	
Fish	Fish pasta	Fish pasta	2.0	
Fish	Fish rice	Hake rice	2.0	
Meat	Fried pork	Fried *febras* (pork)	2.0	
Meat	Grilled pork	Grilled *febras* (pork)	2.0	
Meat	Boiled/stewed pork	Stewed pork with carrot and cabbage	2.0	
Meat	Roast pork	Roast pork loin	2.0	
Meat	Grilled pork	*Entremeada*	1.9	
Meat	Fried pork	Fried pork steaks	1.8	
Vegetarian	Tofu	Sautéed tofu with zucchini	1.7	
Meat	Roast chicken	Roast chicken on skewer	1.7	
Fish	Quiche	Tuna quiche	1.6	
Fish	Baked/stewed fish	Baked sea bream	1.5	
Fish	Grilled fish	Grilled perch	1.5	
Meat	Rice with meat	Chicken rice	1.5	
Vegetarian	Tortilla	Tomato tortilla with cheese	1.3	
Meat	Boiled/stewed pork	Pork *strogonoff*	1.2	
Vegetarian	Pasta	Vegetable lasagna with mushrooms	1.2	
Meat	Baked/roasted turkey	Stewed turkey steak	1.2	
Vegetarian	Quiche	Vegetable quiche	1.1	
Meat	Sausages	Sausage	1.1	
Meat	Pasta with meat	Chicken pasta	1.1	
Meat	Cooked/stewed chicken	Chicken gardener	1.1	
Meat	Burger	Turkey burger	1.0	
Vegetarian	Pastry	Greek spinach and feta puffs	1.0	
Fish	Mackerel	Grilled mackerel	1.0	
Meat	Burger	Chicken burger	0.9	
Fish	Grilled fish	Grilled mackerel	0.9	
Vegetarian	Pastry	Fried leek pastries	0.9	
Vegetarian	Tofu	Fried breaded tofu	0.8	
Fish	Mackerel	Roasted mackerel	0.7	
Vegetarian	Tofu	Tofu curry with vegetables	0.7	
Vegetarian	Eggs	Tomato sauce with eggs and potato	0.7	
Fish	Tuna	Tuna salad	0.7	
Fish	Tuna	Tuna steak	0.7	
Fish	Tuna	Onion tuna	0.7	
Vegetarian	Vegetables	Vegetable curry	0.6	
Vegetarian	Pastry	Fried green beans (*peixinhos da horta)*	0.6	
Vegetarian	Beans	Stewed bean with cabbage	0.5	
Vegetarian	Seitan	Onion seitan	0.5	
Vegetarian	Tortilla	Zucchini tortilla	0.5	
Vegetarian	Pasta	Soy bolognese spaghetti	0.5	
Vegetarian	Quiche	Mushroom and onion quiche	0.5	
Vegetarian	Eggs	Peas with poached eggs	0.5	
Vegetarian	Soybeans	Soy stewed with vegetables	0.5	
Vegetarian	Seitan	Seitan steaks with mushrooms	0.5	
Vegetarian	Vegetables	Leek *à brás*	0.4	
Vegetarian	Soybeans	Soy pie	0.4	
Vegetarian	Bread	*Migas* (cornbread) with greens and black-eyed peas	0.4	
Vegetarian	Pasta	Pasta with stewed vegetables	0.3	
Vegetarian	Seitan	Mediterranean seitan stew	0.2	

The recipes with the highest carbon footprint are those using beef, from the subcategories "fried beef" and "baked/stewed beef," with examples such as "beef steak," "stewed rib," "veal steak," and "veal *jardineira* (mix)" (between 20.0 and 10.0 kg of CO_2eq per individual serving). These are followed by "pasta with meat," with the example of "pasta with minced meat" (also beef, in this recipe's case), and the subcategory "goat/lamb," with the example of the recipe for "stewed goat." The "fish" recipe with the highest carbon footprint (8.6 kg of CO_2eq per individual serving) is from the "prawns" subcategory, with the example of "seafood *cataplana*." These values are in line with the individual ingredients' carbon footprint (Appendix A). The one recipe with a high carbon footprint, but where the main ingredient does not have a high carbon footprint, is "roast turkey" (from the category "poultry" in the food table in Annex A). This is because the recommended amount of turkey for this recipe is very high (575 g), compared to the average amount recommended in animal protein recipes (200 g). The same is true for the recipes for "duck rice" (408 g), "alheira" (a type of sausage, 300 g of "poultry" and 90 g of "pork"), and "baked codfish" (500 g), which are in alignment with the average carbon footprint of all recipes (3.0 kg of CO_2eq).

Aligned between the average (3.0 kg CO_2eq) and median (2.0 kg CO2eq) carbon footprint of all recipes and still with high carbon footprint are fish recipes such as "fried ray," "calamari," "fish stew," and "cuttlefish feijoada."

With a carbon footprint classified as medium (yellow), between the average and median carbon footprint of all recipes, are fish, poultry, and pork recipes. At the median (2.0 kg of CO_2eq) are pork recipes ("fried febras (pork)," "grilled febras (pork)," "stewed pork with carrot and cabbage," "roast pork loin"), poultry ("stewed chicken with carrots and peas"), and fish ("fish pasta" and "hake rice"). The vegetarian recipe with the highest carbon footprint, and below the median, is "sautéed tofu with zucchini" (1.7 kg CO_2eq) in the 51st position, this vegetarian/vegan recipe, without eggs or dairy products, and with the recommended 250 g per person of tofu contributing the most (790 g CO_2eq) to its carbon footprint. Four more vegetarian recipes have a medium (yellow) carbon footprint: "tomato tortilla with cheese," "vegetable lasagna with mushrooms," "vegetable quiche," and "Greek spinach and feta puffs" (all ovolactovegetarian). With the lowest values of carbon footprint classified as medium, besides the vegetarian recipes, are recipes that use mackerel, poultry (ingredients with a carbon footprint classified as medium), and pork, this ingredient with a carbon footprint classified as high, but which the amount of pork recommended as an individual portion in the recipes is low ("sausage" has 90 g of pork, and "pork stroganoff" has 100 g of pork) and in which the remaining ingredients that compose the recipes also have a low carbon footprint.

Within the medium (yellow) carbon footprint classification: 51.4% of the recipes are "meat," 37.1% are "fish," and 14.3% are "vegetarian"; the average carbon footprint of "meat" recipes is 1.6 kg CO_2eq (per individual serving) and median 1.7 kg CO_2eq; the average carbon footprint of the "fish" recipes is 1.7 g CO_2eq and median 1.8 kg CO_2eq; and the average carbon footprint of the "vegetarian" recipes is 1.3 g CO_2eq and median 1.2 kg CO_2eq.

With a carbon footprint classified as low (green), there are only recipes that have low- or medium-carbon footprint ingredients. In the top ten green recipes (with the highest footprint), one recipe is meat ("chicken burger"), 5 are fish ("grilled mackerel," "roasted mackerel," "tuna salad," "tuna steak," "onion tuna"), and 4 are vegetarian ("fried leek pastries," "fried breaded tofu," "tofu curry with vegetables," "tomato sauce with eggs and potato"). Despite tuna as an ingredient having a higher carbon footprint than mackerel (the animal protein with the lowest carbon footprint), tuna recipes recommend a lower than usual protein amount (average 111 g) than mackerel's recipes (average 225 g).

The bottom 15 recipes in green (lowest carbon footprint) are "vegetarian." "Vegetable curry," "fried green beans (*peixinhos da hora*)," and "stewed beans with cabbage" are in the top 3 positions of the bottom 15 recipes (average 0.6 g of CO_2eq). In the bottom 3 positions (lower footprint) are "*migas* (cornbread) with greens and black-eyed peas," "pasta with stewed vegetables," and "Mediterranean seitan stew" (average 0.3 g of CO_2eq, all vegan recipes, i.e., no animal products). Of these 15 recipes, 7 are ovolactovegetarian and the remaining 8 do not contain any food of animal origin (neither eggs nor dairy products).

As for what can be considered more traditional Portuguese dishes (*Receitas Portuguesas—96 Receitas*, n.d.; RRL 2021), the results are also in line with the previous findings. Namely, they have a higher carbon footprint than plant-based meals. In specific, the most traditional Portuguese dishes are "baked codfish," "fried codfish," "codfish in the oven," "duck rice," "stewed goat," and "octopus rice." These have an average carbon footprint of 4.17 kg of CO_2eq, with the highest being 8.7 kg of CO_2eq ("stewed goat") and the lowest being 2.4 kg of CO_2eq ("fried codfish" and "codfish in the oven"). This average is higher than the plant-based meals' carbon footprint mentioned previously of 0.7 kg of CO_2eq.

Lastly, we estimate the carbon footprint of common non-vegetarian meals in which the animal protein was replaced by plant-based protein (recipes which were called "adapted"), in order to analyze hypothesis 3. The quantities of each ingredient of animal protein have not been changed and are from the research resulting from online culinary recipes (mostly on the website Teleculinária.pt). The equivalent vegetable protein was then calculated. The combined average carbon footprint of these "adapted" recipes on the categories of "meat" and "fish" was 0.6 kg of CO_2eq, 6.4 times lower than the carbon footprint of the original recipes, proving hypothesis 3, and in line with the results of hypothesis 1. Table 5 presents a summary of "Sect. 3.".

4 Discussion

The three hypotheses presented were confirmed. Thus, it can be considered that, in Portugal, the transition from common non-vegetarian meals to vegetarian meals would represent, on average, a reduction in GHG emissions derived from food consumption and, consequently, would be a climate change mitigation action.

By analyzing food consumption in Portugal through the common meals that are usually eaten, it is shown that this food consumption includes high carbon footprint foods, such as beef, sheep, crustaceans, and cheese. On the other hand, vegetables and fruits, which have low carbon footprints, are less frequent in the diets in Portugal (Lopes et al. 2018). These are globalized habits and on which it is crucial to focus, rather than just invoke what could be the carbon footprint of food in Portugal, if most foods were produced locally or at a beneficial scale and context (Beal et al. 2023), or what was once the traditional diet in Portugal, but that does not apply to most meals today.

It should be noted that it would be possible to consume mainly non-vegetarian meals and have a lower carbon footprint than if only vegetarian meals were consumed, if the main protein source were foods of animal origin with a low carbon footprint, such as eggs and horse mackerel. Since these are not the usual meal choices in Portugal, and all plant-based foods analyzed, except for tofu, have a lower carbon footprint than animal foods, it is unlikely to observe these cases (Online Resources Annexes E and F).

It was tested whether the results would have been different if the meta-study used as a baseline had been different than that of Poore and Nemecek (2018). We tested Clune et al. (2017) as a baseline study instead, calculating: the average of the three non-vegetarian meals with the highest carbon footprint (7.07 kg CO_2eq and 17.27 kg CO_2eq, respectively, Clune; and Poore and Nemecek); the average of the three vegetarian meals with the highest carbon footprint (1.12 kg CO_2eq and 1.38 kg CO_2eq, respectively); the average of the three non-vegetarian meals with the lowest carbon footprint (0.58 kg CO_2eq and 0.67 kg CO_2eq, respectively); and the average of the three vegetarian meals with the lowest carbon footprint (0.34 kg CO_2eq and 0.27 kg CO_2eq, respectively). The results show similar values in using one study or the other. The exception to this is the average of the three non-vegetarian meals with the highest carbon footprint: 7.07 kg CO_2eq in the meta-study of Clune et al. (2017) and 17.27 kg CO_2eq in the meta-study of Poore and Nemecek (2018). This difference comes mostly from the same ingredient present in the three meals, beef. This could be explained by the following reason: the value of dairy beef was not included in this research; dairy beef is the meat resulting from when the cow is killed for meat after it becomes too old to give milk, but it is estimated that it does not happen often in Portugal (Morais et al. 2018b). In Poore and Nemecek (2018) this is a separate "category" of food, but not in Clune et al. (2017) (rather being included in the beef category). In this research, these values of dairy beef have been removed in Clune et al. (2017) to better compare the averages of beef; if dairy beef had been included in the overall beef category in Poore and Nemecek (2018), the average carbon footprint of beef would have been reduced to 66.4 kg CO_2eq (instead of 99.5 kg CO_2eq).

As previously mentioned, there are inherent limitations in using the meta-study of Poore and Nemecek (2018) of global scope. These limitations were shown in the values of the carbon footprints being higher compared to the values of meta-studies with a European focus (Clune et al. 2017), or compared to the studies that focus on Portugal. Beef, as the main one, being the ingredient with the highest carbon footprint of all, has average values of 99.5 kg CO_2eq/kg in Poore and Nemecek (2018), compared to 28.7 kg CO_2eq/kg in Clune et al. (2017) and 30.1 kg CO_2eq/kg in Morais et al. (2018a). The median values (instead of the average) in all ingredients in Poore and Nemecek (2018) are closer to the average values of the other studies (the median is not available in the other studies), with 60.4 kg CO_2eq/kg, in the case of beef. Another example of a food of animal origin is cow's milk, with an average of 3.2 kg CO_2eq/kg (median of 2.7 kg CO_2eq/kg) in Poore and Nemecek (2018), compared to 1.4 kg CO_2eq/kg in Clune et al. (2017) and 0.8 kg CO_2eq/kg in Morais et al. (2018b). This also happens with plant-based foods. For example, rice, with an average of 4.5 kg CO_2eq/kg (median 3.7 kg CO_2eq/kg) in Poore and Nemecek (2018), compared to 2.7 kg CO_2eq/kg in Clune et al. (2017) and 0.9 kg CO_2eq/kg in APA (2020). Thus, quantitatively, the carbon footprint values of certain ingredients would change, but qualitatively, the results of foods with higher and lower carbon footprints remain the same. That is, animal-based foods would still be the ones with the highest carbon footprint (led by beef) and plant-based foods would still be the ones with the lowest carbon footprint. Thus, the meta-study of Poore and Nemecek (2018) was highlighted for the advantages mentioned previously.

A brief nutritional functional unit analysis of the food items was included in this research, specifically for protein per 100 g of mass/food item. This is critical to allow plant-based meals to be a viable nutritionally balanced option to be adopted by consumers. This was not revealed as an impediment factor, since most protein-rich plant-based food items, like lentils and beans, have similar nutritional functional

Table 5 Summary of the analysis, variables, central tendency and dispersion, and results of each hypothesis for the common meals

No.	Hypothesis	Analysis	Simple variables	Central tendency and dispersion	Results
1	In Portugal, common vegetarian meals have, on average, a lower carbon footprint than common non-vegetarian meals	Average carbon footprint for “meat” and “fish” categories compared to average carbon footprint for “vegetarian”	kg of CO_2eq per recipe “meat” category; kg of CO_2eq per recipe “fish”; kg of CO_2eq per recipe “vegetarian”	Averages: 3.9 kg CO_2eq per recipe for “meat” and “fish” categories; 0.7 kg CO_2eq per recipe “vegetarian”	5.5 times lower
2	There is a wide range of carbon footprint values for vegetarian meals in Portugal	Percentiles, median, standard deviation, and average carbon footprint of “vegetarian” recipes	kg of CO_2eq per recipe in the “vegetarian” category	Average: 0.7 kg of CO_2eq per recipe in the category “vegetarian”; median: 0.8 kg CO_2eq per recipe “vegetarian”; 5th percentile: 0.2 kg of CO_2eq per recipe of the “vegetarian” category; 95th percentile: 1.7 kg of CO_2eq per recipe of the “vegetarian” category; standard deviation: 0.36 kg of CO_2eq per recipe in the “vegetarian” category	5th percentile is 8.5 times smaller than the 95th percentile
3	There are conventional non-vegetarian meals in Portugal that, adapted to be vegetarian meals, can considerably reduce their carbon footprint	Combined average carbon footprint of “adapted” recipes in the categories “meat” and “fish” compared to the combined average of the carbon footprint of the original recipes of the categories “meat” and “fish”	kg of CO_2eq per “adapted” recipes of “meat” and “fish” categories; kg of CO_2eq per recipe of “meat” and “fish” categories	Combined averages: 0.6 kg CO_2eq per recipe for “adapted” recipes in “meat” and “fish” categories; 3.9 kg CO_2eq per recipe in “meat” and “fish” categories	6.4 times lower

value as protein-rich animal foods, such as beef, fish, and even more than poultry.

Besides this quantity (grams of protein per 100 g of food item mass), the quality of that protein was also a factor to take into account, the most relevant being the bioavailability of essential amino acids (Beal et al. 2023; McAuliffe et al. 2023), since animal-based foods usually rank higher in this factor, i.e., "contain higher densities and more bioavailable forms of essential amino acids (EAAs) than those contained in PSFs [Plant Sourced Foods]" (Beal et al. 2023). The higher-protein content plant-based foods reviewed in this research have similar levels to animal-based foods of this bioavailability, namely soy-based products like tofu and soymilk, and unlike "ultraprocessed foods that include plant protein isolates (e.g., plant-based burgers)" (Beal et al. 2023), such as the Beyond Burger™, which are suggested to be less bioavailable than pasture-raised beef (Pham et al. 2022). Studies incising on these types of ultraprocessed plant-based foods are still few, due to these products' recent creation and consumer market availability, and thus were not considered in this research.

Besides using tofu and soy-based products in plant-based meals to ensure the bioavailability of essential amino acids, it is also suggested that as an alternative there is a "daily consumption of foods with complementary EAA profiles (e.g., combining beans and rice)" (Beal et al. 2023). The results from this research are in line with this, since plant-based food items like rice, legumes, wheat, and others are revealed to have a low carbon footprint. We add that this has always been the food tradition in many cultures worldwide, for example, the aforementioned beans and rice in Mexico and Brazil, among others (Wilk and Barbosa 2012); rice and lentils in Iran, India, Egypt, and Pakistan, among others (Singh and Singh 2014); and hummus and bread in Middle East, North Africa, and the Mediterranean, among others (Martin 2023), and remains especially relevant in low to medium-income countries.

For low-income countries, it is suggested in some studies that "any populations in Sub-Saharan Africa and South Asia could benefit from increased consumption of ASFs [Animal Sourced Foods] through improved nutrient intakes and reduced undernutrition" (Beal et al. 2023), or generally in the "global South and vulnerable populations of high-income countries (e.g., children, women of reproductive age and elderly)" (McAuliffe et al. 2023), rather than solely plant-based foods. This can be valid, and it was not the geographical focus of this research. However, the opposite is true for high-income countries, such as Portugal, where our research is focused, where meat consumption should be decreased for health and environmental reasons (Beal et al. 2023; Sun et al. 2022). We also agree with McAuliffe et al. (2023) that this reduction is possible and nutritious only under "appropriate dietary consideration" (McAuliffe et al. 2023), especially if that reduction is total, as of a vegan diet.

The use of LCAs is complex but possible and advisable, to reach accurate food items' carbon footprint, as opposed to simply "raw materials, meals and/or diets" (McLaren et al. 2021). Due to the small team and lack of funding for this research, the carbon footprint values reached were an estimation, and it was not feasible to include all the suggestions from the in-depth review of McLaren et al. (2021), despite some having been done in this research, such as using studies with LCAs that include the nutritional functional unit, besides only "quantifying the environmental impacts based on mass or volume based quantities of foods" (McLaren et al. 2021, p. 2).

It is also suggested that LCAs, regarding the bioavailability factor "should discuss the complementarity of amino acid balances at the meal-level, as a minimum, rather than the product level when assessing protein metabolic responses of consumers" (McAuliffe et al. 2023). Although this was not the focus of this research, we do agree on the focus at the meal level, like this research, rather than product/food item level, in similar research.

It should also be acknowledged that all LCA estimations used are based on the present food system. With a shift towards a vegetarian diet, some of the hypotheses in the LCAs would not be met. For example, there would be different uses for the current agricultural products, such as large-scale livestock feed or the meat from dairy systems (dairy cows), given that the dairy livestock would probably serve no purpose. This is valid for most LCAs, if one moved towards a more plant-based (or even a more meat-based) food system, as most products would lose some of the present uses, and gain others, which are currently not economically viable.

Given that it is beyond the present work to address such a difficult scenario, our estimates should be interpreted as those of a marginal change towards a more plant-based food system.

It is also acknowledged that in this research an attributional LCA approach was used (as opposed to a consequential LCA approach), thus relative to "when there is no specific decision at hand" (Tillman 2010). It was intended, from this research, to communicate the results in a format that might lead consumers in Portugal to reduce their food carbon footprint, but no consequences as such were deepened and actioned. This implies that the conclusions of this research, to be formally valid as a climate mitigation method, specifically within the nationally determined contributions for climate action (UNFCCC 2022), would need further development. For example, to present this research's results in participatory sessions with different Portuguese school communities' stakeholders (such as municipality members, students, families, teachers, cooks, and others), towards the shift to a weekly plant-based meal for all students, as this is already being done in Portugal in selected locations (GFN 2022). Another example is to partner with the consumer protection association in Portugal, DECO, to analyze what would be the cost variation for consumers if a determined percentage of their protein was plant-based, rather than animal-based, while simultaneously aiming to localize the production of plant-based proteins, through government incentives and regulation, as suggested by Galli et al. (2020).

A further next step from our research could be, aiming to reduce food's carbon footprint in Portugal, updating the national dietary guidelines (FAO 2023), to integrate the environmental impact of food. The wheel guide (FCNAUP 2003) being the most relevant should show "protein" instead of "meat, fish and eggs," as one of its categories. This would allow consumers to select their preferred protein sources, with a lower environmental impact, if choosing plant-based proteins, rather than mandating they should be eating animal products, this being the default shown protein source.

It is relevant that the data from IAN-AF 2015–2016 continues to be analyzed and deepened to inform the state of food in Portugal, including the environmental impact of food. In deepening the results of this research, it will be important to estimate the carbon footprint of consumers' food diaries. This will add more robustness, by using the amount of each ingredient (in grams), consumed in each meal per individual, rather than estimating these quantities, through similar cooking recipes, as was done in this research.

Lastly, the environmental impact of food in Portugal is not restricted to GHG emissions, thus measurable by the carbon footprint. Food has an environmental impact not only, but also, on biodiversity (Carapeto et al. 2020), due to intensive crops, among other factors; water availability (Saldanha and Jerónimo 2020), due to agriculture and livestock, among other factors; and other areas (eutrophication, acidification) that, not being the focus of this research, are relevant to mention, for the benefit of an informed framework.

5 Conclusion

This research aimed to find out if, in Portugal, common vegetarian meals have a lower carbon footprint than common non-vegetarian meals; and to posteriorly communicate the results in an immediate, comparable, relevant, and appealing format that might lead Portuguese consumers to reduce this food carbon footprint of theirs.

The results reveal that most vegetarian meals eaten in Portugal have a lower carbon footprint than non-vegetarian meals eaten in Portugal. In addition, if in Portugal's meals animal protein was replaced by plant-based protein, their carbon footprint would be substantially smaller.

The format utilized to communicate the results was the traffic light system, which has the potential to lead Portuguese consumers to reduce their food carbon footprint.

Despite the limitations presented in "Sect. 4," the three general hypotheses of this research have been confirmed. Namely, in Portugal, common vegetarian meals have, on average, a lower carbon footprint than common non-vegetarian meals (hypothesis 1), specifically 5.5 times lower; there is a wide range of carbon footprint values for vegetarian meals in Portugal (hypothesis 2), specifically, the 5th percentile is 8.5 times smaller than the 95th percentile; and there are conventional non-vegetarian meals in Portugal that, adapted to be vegetarian meals, can considerably reduce their carbon footprint (hypothesis 3), specifically a 6.4 times reduction. Thus, it can be concluded that vegetarian food is a potential solution for food's environmental sustainability in Portugal.

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Declarations

Competing interests The authors declare no competing interests.

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