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Quantifying Farm-to-Fork Greenhouse Gas Emissions for Five Dietary Patterns Across Europe and North America: A pooled analysis from 2009 to 2020

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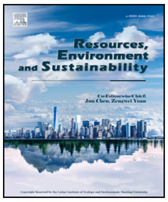

Review article

Quantifying farm-to-fork greenhouse gas emissions for five dietary patterns across Europe and North America: A pooled analysis from 2009 to 2020

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ABSTRACT

Dietary patterns are inherently related to greenhouse (GHG) emissions via agricultural practices and food production systems. As the global population is predicted to increase from 8 billion (current) to 9.6 billion by 2050 added pressure will be placed on existing agricultural systems, resulting in increased GHG emissions thus exacerbating climate change. Therefore, there is an urgent need to understand present-day dietary patterns to shift to sustainable and healthy diets to mitigate GHG emissions and meet future climate targets. However, no review or pooled analyses of dietary pattern emissions from a farm-to-fork perspective has been undertaken to date. The current study sought to i) identify the current dietary habits within high-income regions from 2009 to 2020 and ii) quantify the GHG emissions associated with these dietary patterns via a global systematised review and pooled analysis. Twenty-three peer-reviewed studies were identified through online bibliographic databases. Dietary patterns are being examined based on fixed inclusion/exclusion criteria. Five dietary patterns were identified in the review with their mean GHG emissions: high-protein diets (5.71 CO_2eq kg person^{-1} day^{-1}), omnivorous diet (4.83 CO_2eq kg person^{-1} day^{-1}), lacto-ovo-vegetarian/pescatarian diet (3.86 CO_2eq kg person^{-1} day^{-1}), recommended diet (3.68 CO_2eq kg person^{-1} day^{-1}), and the vegan diet (2.34 CO_2eq kg person^{-1} day^{-1}). The lacto-ovo-vegetarian/pescatarian diet was associated with significantly lower emissions than both the omnivorous and high-protein dietary patterns, with -22% and -41% GHG emissions, respectively. The high-protein dietary pattern exhibited significantly higher GHG emissions than other dietary patterns. Geographically, significant statistical differences ($p = 0.001$) were only reported for the omnivorous diet between North America and Europe. Findings reveal that GHG emissions vary based on dietary patterns and have the potential to be reduced by shifting dietary patterns, which benefits the environment by lessening one of the drivers of climate change.

Contents

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1. Introduction

Previous and ongoing research leaves little doubt that dietary patterns are inherently related to greenhouse (GHG) emissions, and thus a driver of climate change, via agricultural practices and food production systems (Biesbroek et al., 2018; Hallstrom et al., 2015; Mertens et al., 2020; Springmann et al., 2018). In 2019, global anthropogenic emissions equated to 54 billion metric tonnes of CO_2 equivalents, of which 31% (16.5 billion metric tonnes) derived from agri-food systems (Tubiello et al., 2021). Moreover, livestock production, a large component of the agricultural sector, is associated with approximately 14.5%–18% of all anthropogenic GHG emissions (Chaudhary and Tremorin, 2020; Farchi et al., 2017; Mogensen et al., 2020; Ridoutt et al., 2021; Seves et al., 2017). The global population is predicted to reach 9.6 billion by 2050 (FAO, 2016) from the current 8 billion people (UN, 2022), thus placing significant added pressure on existing food systems (Chaudhary and Tremorin, 2020; Clark and Tilman, 2017; Mertens et al., 2020). Over the same period (i.e.,2020–2050), global dietary patterns are expected to increasingly shift towards animal-derived produce, with meat and milk consumption predicted to increase by 73% and 58%, respectively (FAO, 2011). Increased atmospheric GHGs are increasing the average global temperature and exacerbating climate change (Aydinalp and Cresser, 2008; Fresan et al., 2019; Gonzalez-Garcia et al., 2020; Hallstrom et al., 2015; Mertens et al., 2020; Springmann et al., 2018). These excessive GHG emissions from agricultural systems need to curtailed in order to meet the Paris Agreement and the United Nations Sustainable Development Goals target of limiting global warming to less than 2 °C (UN, 2015). Climatic shifts resulting from climate change and global warming may substantially alter crop yields by creating a mismatch between existing agricultural systems and historical climatic conditions (Aydinalp and Cresser, 2008; Campbell et al., 2016; Fresan et al., 2019; Gonzalez-Garcia et al., 2020). Concurrently, rising sea levels may result in a loss of farmland via coastal flooding and increasing groundwater salinity, with livestock and dairy production also at risk due to shifting forage crop patterns and the increasing geographical range of disease vectors, such as ticks (Aydinalp and Cresser, 2008; Mahato, 2014; Zhang et al., 2022).

The concept of wholescale dietary pattern alteration, rather than individual food items, to reduce GHG emissions has received increasing attention in the past decade (Candy et al., 2019; Corrado et al., 2019; Ernstoff et al., 2019; Esteve-Llorens et al., 2020; Grosso et al., 2020). This is especially important in high-income countries, which represent 16% of the global population but generate 26% of global agricultural emissions (IPCC, 2014). Specific dietary patterns have been associated with high agricultural emissions, particularly the omnivorous “Western” diet which is prevalent in North America and Europe and is characterised by high consumption of animal-based products and an excess of daily recommended caloric intake (Azzam, 2021; Westhoek et al., 2014). This diet is reported as being environmentally unsustainable and associated with obesity (Candy et al., 2019; Chaudhary and Tremorin, 2020). However, high-income countries could potentially significantly reduce GHG emissions by transitioning dietary patterns (Candy et al., 2019; Chaudhary and Tremorin, 2020; Springmann et al., 2018). For example, Chaudhary and Tremorin (2020) report that by replacing 33% of ground beef with cooked lentil puree in Canada, the environmental footprint from farm to retail could be decreased by approximately 33% (Chaudhary and Tremorin, 2020). Reducing the quantity of meat being consumed has also been shown to reduce diet related GHG emissions (Bassi et al., 2022; Zhang et al., 2022). Bassi et al., has shown that from the years 2003 to 2018, Americans ate 1.78 less grams of beef yearly which equated to 70.7 g CO_2e per capita per day per year and accounted for almost half of observed yearly GHG savings across diets (Bassi et al., 2022).

Lifecycle assessment (LCA) based approaches are frequently utilised to evaluate the environmental impact of individual food product lifecycle stages, including production, processing, packaging, transportation (to and from retail), cooking, and disposal (Aleksandrowicz et al., 2016; Hallstrom et al., 2015). LCA system boundaries (i.e., conceptual delineations dividing the target system being studied from items not included in the study) must be specified as each step in the product lifecycle produces varying emissions (Aleksandrowicz et al., 2016; Hallstrom et al., 2015). For example, previous studies have reported that the majority (66%–86%) of diet-related GHG emissions occur during the production stage (Corrado et al., 2019; Kim et al., 2020), with 15%–21% attributed to food preparation (including cooking), and 11%–13% associated with food waste arising from preparation and consumption (Corrado et al., 2019; Hitaj et al., 2019). Thus, a thorough awareness of diet-related emissions from production to consumption (i.e., cradle-to-grave and farm-to-fork) is crucial to understanding food systems in their entirety.

While previous reviews by Aleksandrowicz et al. (2016) and Hallstrom et al. (2015) have quantified GHG emission reductions as they relate to several dietary patterns, the scope of these studies included a range of LCA system boundaries (e.g., farm-to-farm gate, farm-to-market gate, farm-to-fork, and cradle-to-grave) (Aleksandrowicz et al., 2016; Hallstrom et al., 2015). This broad scope can be primarily attributed to (1.) the small number of high-income country studies focusing on the environmental impact of dietary practices and (2.) the lack of standardisation in dietary LCAs (Hallstrom et al., 2015). Notwithstanding, while research assessing the environmental impacts of actual and theoretical diets in high-income countries from a farm-to-fork perspective has increased in recent years, to date, these studies have yet to be pooled and analysed.

The current study sought to address this notable gap by examining five pre-defined dietary patterns within high-income countries in Europe and North America and statistically characterising their environmental impacts using calculated GHG emissions (CO_2 eq kg person^{-1} day^{-1}) as the primary environmental indicator (Reynolds et al., 2019). High-income countries are also located in Asia and Oceania, however, these areas are geographically wide-ranging and populated by people of diverse cultures, ethnicities, and dietary components, as shown by significant regional differences in dietary guidelines and the prevalence of lactose intolerance in Asia (Herforth et al., 2019; Horwood et al., 2019). These reasons may potentially include some inaccuracies, therefore, the current study focused on high-income countries in Europe and North America. To the author’s knowledge, this is the first pooled analysis of recorded and hypothetical dietary patterns across high-income countries from a farm-to-fork perspective with respect to GHG emissions. By examining the environmental impacts of existing dietary patterns from a farm-to-fork perspective, increasingly sustainable dietary patterns may be identified (or developed), thus assisting the successful realisation of the Sustainable Development Goals (SDGs), the Paris Climate Agreement, and the European Commission’s European Green Deal.

2. Materials and methods

2.1. Literature identification

The scoping review protocol used in the present study was developed from several previous high-impact reviews (Andrade et al., 2018; Chique et al., 2021; Hynds et al., 2014; Sargeant et al., 2006). A

Table 1
Search themes and terms used for initial and final literature search and inclusion and exclusion criteria applied to studies to determine eligibility for data extraction and analyses.

Term classification	Description	Search terms
Population:	Residents of high-income countries	High-Income Country, High-Income Countries
Diet:	Dietary habits	Diet(s), Diet Quality, Human Diets, Human Diet, Dietary Habits, Food Consumption, Nutrition, Food Habits, Dietary Choice, Food, Dietary Pattern Analysis, Dietary Patterns, Vegan, Vegetarian, Semi-Vegetarian, Pesco-Vegetarian, Pescatarian, Omnivore, Omnivorous Diet, Flexitarian, Plant-based foods
Agent and consequence:	Environmental impact of dietary patterns	Environmental impact, Food Waste, Climate Change, Ecosystem, Environment, Sustainable, Sustainability, Greenhouse, Life Cycle, Footprint, Energy Use, Water Use, Biodiversity, LCA, Life Cycle Assessment, GHG, GHGe, GHG emission(s), Global warming potential
Final search terms:	Web of science	TS = ((“omnivor*” OR “vegetarian*” OR “semi-vegetarian*” OR “plant-based diet*” OR “plant-based food*” OR “flexitarian*” OR “vegan*” OR “diet* pattern*”) AND (“environment* impact” OR “land use” OR “water use” OR “global warming potential”))
	Scopus	TITLE-ABS-KEY ((“omnivor*” OR “vegetarian*” OR “semi-vegetarian*” OR “plant-based diet*” OR “plant-based food*” OR “flexitarian*” OR “vegan*” OR “diet*pattern*”) AND (“environment* impact” OR “land use” Or “water use” OR “global warming potential”))

Inclusion criteria	Exclusion criteria
Study type: All primary research articles (peer-reviewed).	**Study type:** Academic reviews, surveillance reviews, book chapter(s), conference proceedings
Language: English	**Language:** non–English
Population: Average healthy urban and rural youth and adult (2 years or older) populations	**Population:** Specific groups (e.g., infants, people with health problems, men only, women only). *Diets for specific groups may have special diets tailored to that group and not representative of the total population.*
Region: High-income countries	**Region:** Low- & middle-income countries and high-income countries in Asia and Oceania
Event/Outcome: The study assesses dietary greenhouse gas emissions, land-use change, and water use	**Event/Outcome:** greenhouse gas emissions from individual food items
Study design: LCA, with system boundaries between production at the farm level to when the food item leaves the farm (farm to farm gate)/is prepared for consumption (farm to fork)/is purchased at the market (farm to retail gate), models based on LCA, diets based on survey data (food frequency questionnaire), food balance sheets (FBS), and national recommendations	**Study design:** Discussion/commentary, Reviews
Period: 2000 to present	

primary research question was developed to guide the scoping review and analyses, as follows:

“*What are current dietary habits within high-income regions, and what are the GHG emissions, measured in CO_2 equivalents, associated with these dietary patterns?*”

The online databases Scopus and Web of Science were the primary bibliographic sources used to identify relevant studies. Boolean positional operators (“AND”, “OR”) and wild card operators (*, $, “”) were implemented in conjunction with relevant search terms (Table 1). Within Web of Science, the field tag “TS” was used to keep the search focus on the article’s topic, and for Scopus, “TITLE-ABS-KEY” was used as the search string to identify target terms in the title, abstract, and keywords. Prior to commencing the final search, several mock searches were conducted to confirm the search methodology’s repeatability and capacity to accurately identify all target studies.

Article screening, selection, and identification

Potentially relevant articles from initial searches were subjected to four distinct selection phases: identification, screening, exclusion, and eligibility (Fig. 1). In Phase 1 (identification), a total of 510 deduplicated records were identified from Scopus and Web of Science through a title, abstract, and keyword search. For Phase 2 (screening), each record was subject to a title and abstract screening based on eligibility criteria (Table 1). These records were then independently screened for eligibility (i.e., included or excluded for full-text screening) by all authors independently. In Phase 3 (eligibility), all remaining records were subject to a full-text screening based on predetermined inclusion and exclusion criteria (Table 1).

The primary inclusion criteria employed were: (i) primary peer-reviewed research articles, (ii) English language, (iii) comprising an average healthy population (i.e., no cohorts comprised primarily of persons with underlying health conditions, infants, or pregnant women), (iv) studies undertaken in high-income countries as classified by the World Bank (i.e., gross national income > US$12,615 based on World Bank data WB, 2021), (v) studies assessing GHG emissions as they directly relate to dietary patterns (vi) system boundaries specified between production at the farm level or food production stage to consumption and disposal by the consumer (farm-to-fork), (vii) diets based on survey data (food frequency questionnaire and 24 h recalls), food balance sheets (FBS) presenting a comprehensive picture of a country’s food production and consumption during a target reference period, or nationally recommended (hypothetical) diets, and (viii) studies published during or after 2009 to ensure relevance and comparability between studies.

Exclusion criteria included: (i) secondary research articles and grey literature (e.g., literature reviews, book chapters, conference papers), (ii) papers not published in English, (iii) study populations comprising specific sub-cohorts (e.g., infants, sub-populations characterised by the presence of one or more underlying health conditions, specific gender) which may not represent the population as a whole, and (iv) studies from low- and middle-income countries and high-income countries in Oceania and Asia as this study sought to examine dietary patterns across countries with similar physical, cultural, and dietary backgrounds (Herforth et al., 2019; Horwood et al., 2019; McMichael et al., 1980). Additional pertinent literature not initially identified via Phases 1–3 were captured through manual screening of the included articles’ bibliographies throughout phases 1–2 (n = 8) (Fig. 1).

2.2. Data extraction and classification

All potentially relevant data fields in the context of the developed research question were extracted after identification of studies for inclusion (n = 23). Within the current study, an article is defined as

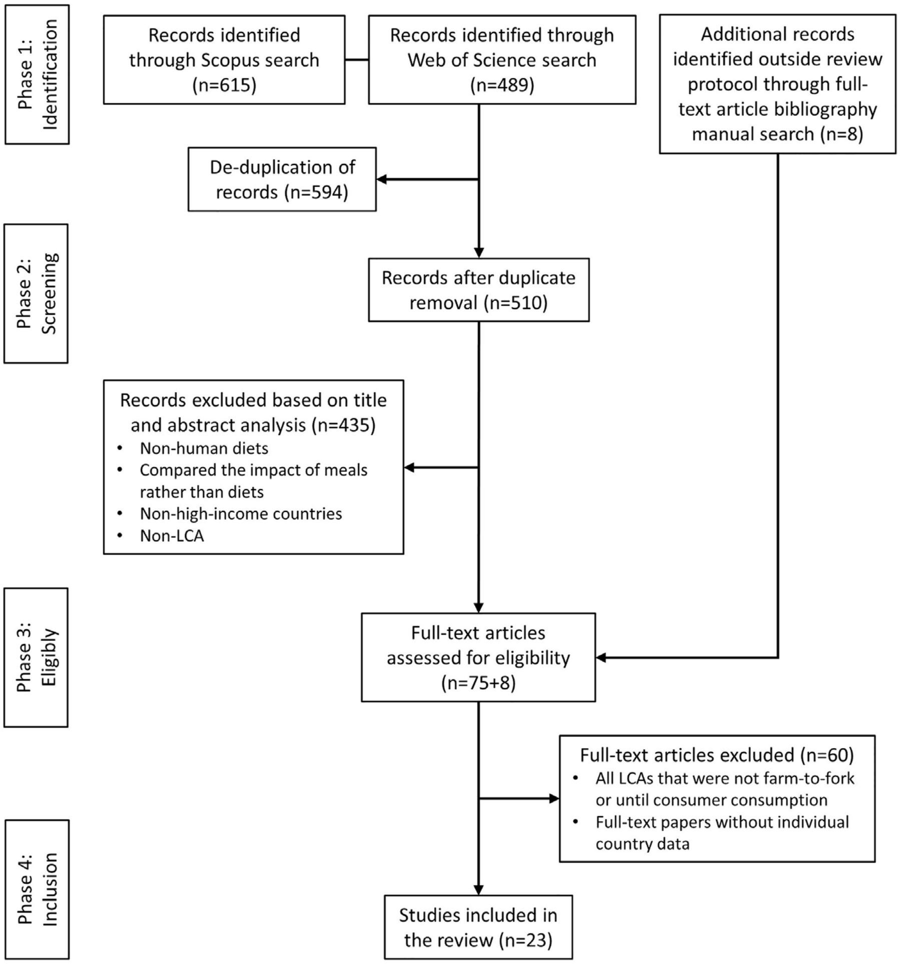

Fig. 1. Diagram summarising the review protocol used for the current study with the four distinct review phases (Identification, Screening, Eligibility, Inclusion) delineated on the vertical axis.

an individual publication which reports study findings from a specific region and population. Study records were extracted from each article for a specific dietary pattern. Extracted data fields were delineated into seven main categories: (i) bibliographic details, (ii) location, (iii) type of diet(s), (iv) study details (study population, year of initial diet study), (v) daily energy intake per person (kcal $person^{-1}$ day^{-1}), and (vi) daily GHG emissions per person (CO_2eq kg $person^{-1}$ day^{-1}).

The LCA methodological approach to dietary scenario analysis can affect the quality and consistency of analyses and subsequent findings. For example, varying functional units (FU) and system boundaries may impact the final quantifiable variable(s), making comparison difficult (Hallstrom et al., 2015). In LCA, the FU is the reference base describing the studied object's function, i.e., a specific food product's CO_2eq emissions, thus enabling comparison between different systems (Hallstrom et al., 2015). Since there was little standardisation with measured FUs, data fields were standardised by unit conversion for final data extraction where applicable, with all units converted to CO_2 equivalents per capita per day (CO_2eq kg $person^{-1}$ day^{-1}).

The lack of standardisation in LCA nomenclature for food system analysis also required resolution. The scope of this review focused on the farm-to-fork boundary, including all phases of agricultural production, processing, transport, and food preparation. Many studies referred to this system boundary with different naming conventions, including "cradle-to-consumer", "cradle-to-mouth", and "farm-to-plate". Therefore, the description of system boundaries and the sources of emissions were considered in the selection of articles for this review, and system boundaries adjudged equivalent to farm-to-fork were included. Farm-to-farm gate and farm-to-market gate were the other prominent system boundaries identified in the screened papers. However, only farm-to-fork was used for data analysis (Table 1).

Dietary patterns are not universally defined; in the interests of analytical comparability, diets from included articles were categorised based on their within-study description and dietary composition similarly to the methodology of past reviews by Aleksandrowicz et al. (2016) and Hallstrom et al. (2015). Five dietary patterns were proposed for analysis:

i. **High-protein:** diets that included daily meat consumption and meat consumption ≥100 grams/day as defined by Scarborough et al. (2014)
ii. **Lacto-ovo-vegetarian/pescatarian:** vegetarian and pescatarian diets that may or may not include consumption of dairy, eggs, and fish
iii. **Omnivorous:** baseline and recorded diets including both red and non-red meat consumption
iv. **Recommended:** diets that are nationally recommended, healthy guidelines, Mediterranean and Atlantic diets, partial meat substitution by plant-based products, and decreased meat and dairy consumption
v. **Vegan:** diets that do not include animal-based products

In order to identity the maximum number of studies during the screening phase, studies in high-income countries within North America and Europe were extracted by manually inputting and searching country names and geographic regions in concurrence with other study-related search terms. To enable a more in-depth investigation of the geographic distribution of identified dietary patterns, identified studies were categorised into five distinct regions based on the United Nations Statistics Division (UNSD) categorisation of global regions:

I. **Eastern Europe:** Czech Republic
II. **Northern Europe:** Denmark, Finland, Sweden, and the United Kingdom
III. **Southern Europe:** Italy, Portugal, and Spain
IV. **Western Europe:** France and the Netherlands
V. **North America:** Canada and the United States of America

As variations were identified with respect to kcal consumption between differing dietary patterns and regions, GHG emissions were standardised based on a 2000 kcal per day intake (i.e., GHG emissions per 2000 kcal). The denominator used for standardisation (2000 kcal per day) was based on the United States Food and Drug Administration general guide for nutrition advice and the guidelines for daily energy intake for adults in the United Kingdom (NHS, 2019; Scarborough et al., 2014; USFDA, 2020)

2.3. Statistical analysis

Pooled arithmetic means, medians, maximums, minimums, and standard deviations for dietary GHG emissions and daily kcal consumption were calculated for all five dietary patterns. For all extracted dietary emissions values, the observed means and the standardised means were subject to statistical tests. Homogeneity of variance(s) was tested using Levene's test — in the case of unequal variance, Welch's test (i.e., unequal variances t-test) was employed to identify the presence of statistically significant differences between categorical and scale (continuous) variables, otherwise one-way ANOVA was used (i.e., equal variance confirmed). Tukey's Post-Hoc Honest Significant Difference (HSD) test was used to compare individual category means where statistical significance was found via Welsh's test or one-way ANOVA (i.e., identify source of between-groups difference). All analyses were conducted using SPSS (Statistical Product and Service Solutions) V28, with statistical significance set at 5% ($\alpha = 0.05$) by convention. The percentage difference between all variables shown in Table 4 and all subsequent tables was calculated using the percentage difference formula.

$$\text{Percentage difference formula: } \left(\frac{|V1 - V2|}{\left[\frac{V1+V2}{2}\right]} \right) * 100 \qquad (1)$$

3. Results

3.1. Overview of included studies

A total of 23 articles fulfilled all specified inclusion criteria Tables (Tables 3 & 4). Mertens et al.'s (2020) study comprised dietary records from four different countries (Czech Republic, Denmark, France, Italy); thus, 26 regionally specific dietary studies were included for analyses, each of which represented an individual study focusing on a single region (Table 2). Subsequently, 99 unique GHG emissions records and 92 kcal consumption records relating to individual dietary patterns were extracted. A majority of identified studies investigated the recommended (21/26; 80.8%) and omnivorous diets (20/26; 76.9%), while half of the identified studies examined the lacto-ovo-vegetarian/pescatarian diet (13/26; 50%). Vegan (5/26; 30.8%) and high-protein (8/26; 19.2%) diets were the least frequently investigated. As shown (Table 3), the literature spanned 11 years (2009 to 2020), with over half (15/26; 57.7%) of identified studies published during the three-year period 2018 to 2020. European countries were most frequently featured (23/26; 88.5%). France, Spain, and the Netherlands were the most recurrent geographic locations within the European region, with four studies (15.4%) each. Study participant number was reported in approximately three-quarters of all included studies (18/26; 78.3%), with a total (i.e., pooled) study population of 177,736 participants (Table 3). The mean reported study sample was 9874 participants, with a minimum and maximum of 153 participants (Rosi et al., 2017) and 55,504 participants (Scarborough et al., 2014), respectively.

3.2. Dietary patterns and kcal consumption

A pooled mean daily kcal consumption of 2263 kcal person^{-1} day^{-1} was found across all dietary records. The omnivorous diet exhibited the highest calculated mean daily kcal consumption of 2288 kcal person^{-1} day^{-1}, while the high-protein diet had the lowest calculated mean of 2222 kcal person^{-1} day^{-1} (Table 5). The Dutch study by Biesbroek et al. (2018) contained the lowest kcal consumption record which was associated with a recommended diet (1903 kcal person^{-1} day^{-1}). The maximum value of 3017 kcal person^{-1} day^{-1} was associated with an omnivorous dietary record reported in the Portuguese (Southern Europe) study by Esteve-Llorens et al. (2020). Northern Europe had the lowest calculated mean of 2100 kcal person^{-1} day^{-1} relating to the Lacto-ovo-vegetarian/pescatarian diet; conversely, the highest calculated mean was associated with Southern Europe's omnivorous diets at 2470 kcal person^{-1} day^{-1}.

No statistically significant difference between the five dietary patterns and calculated daily kcal consumption means were found ($F(4) = 0.337$, $p = 0.853$). However, upon examination of regional daily kcal consumption differences for each dietary pattern and the regional differences in kcal consumption, the lacto-ovo-vegetarian/pescatarian diet ($F(4) = 4.032$, $p = 0.022$) was significantly different. Post Hoc Tukey's HSD Tests indicate that the mean daily kcal consumption associated with the lacto-ovo-vegetarian/pescatarian diet is significantly different between Western (2328 kcal person^{-1} day^{-1}) and Northern Europe (2100 kcal person^{-1} day^{-1}) (Table 4).

3.3. Dietary patterns and GHG emissions

A mean calculated GHG emission of 4.10 CO_2eq kg person^{-1} day^{-1} was calculated across all 99 dietary records (i.e., pooled mean of high-income countries) (Fig. 2). High-protein diets exhibited the highest calculated mean (5.71 CO_2eq kg person^{-1}day^{-1}). This was followed by the omnivorous diet (4.83 CO_2eq kg person^{-1} day^{-1}), the lacto-ovo-vegetarian/pescatarian diet (3.86 CO_2eq kg person^{-1} day^{-1}), the recommended diet (3.68 CO_2eq kg person^{-1} day^{-1}), and the vegan diet (2.34 CO_2eq kg person^{-1} day^{-1}) (Table 6) ($F(4) = 14.73$, $p < 0.001$). The record with the highest individual GHG emission value was reported for the omnivorous diet (8.74 CO_2eq kg person^{-1} day^{-1}) in a study from the United States with 9762 participants (Hitaj et al., 2019). Conversely, the record with the lowest identified value was 1.41 CO_2eq kg person^{-1} day^{-1} associated with a Spanish vegan dietary record (participant number not reported) (Abejon et al., 2020). As shown (Table 6), all four "non-vegan" dietary patterns exhibited significantly higher GHG emissions than the vegan diet, ranging from +45% (recommended) to +84% (high-protein). Likewise, the lacto-ovo-vegetarian/pescatarian diet was associated with significantly lower GHG emissions when compared to the omnivorous and high-protein dietary patterns, with −22% and −39% GHG emissions, respectively. Conclusively, the high-protein dietary pattern exhibited significantly higher GHG emissions than other dietary patterns, with +39%, +43%, and +89% higher GHG emissions than the lacto-ovo-vegetarian/pescatarian diet, recommended diet, and vegan diet, respectively.

Regional GHG emissions for each dietary pattern were also examined; one-way ANOVA followed by Tukey's HSD Test indicates that the omnivorous diet ($F(3) = 8.050$, $p < 0.001$) was the only dietary pattern that was statistically different between the regions. Calculated mean GHG emissions were significantly different between the European

Table 2

Primary descriptive characteristics of the included 23 articles and 26 regionally specific dietary studies ranging from 2009 to 2020, including year of publication, country where the study was conducted, number of unique dietary GHG emissions records, number of study participants, study cohort and the year(s) the study cohort was investigated.

Country	No. of dietary GHG records	Population	Study cohort	Study period	Reference
Spain	6	NA[a]	Food-Away-From-Home (FAFH) report by the Spanish Ministry of Agriculture, Fisheries, and Food and diets based on the recommendations given by dietary guidelines	2018	Abejon et al. (2020)
Spain	3	7000	In- and out-of-home food consumption surveys by the Spanish Ministry of Agriculture and Fishery, Food and Environment	2006–2016	Batlle-Bayer et al. (2019)
France	2	1903	Second French Individual and National Study on Food Consumption cross-sectional dietary survey (INCA2)	2005–2007	Barre et al. (2018)
Netherlands	5	36,209	The European Prospective Investigation into Cancer—Netherlands (EPIC-NL)	1993–1997	Biesbroek et al. (2018)
Netherlands	3	35,057	The European Prospective Investigation into Cancer—Netherlands (EPIC-NL)	1993–1997	Biesbroek et al. (2014)
Netherlands	8	3819	National Food Consumption Survey in the Netherlands	2007–2010	Broekema et al. (2020)
Denmark	6	NA[a]	Food Balance Sheet, assembled by the Food and Agriculture Organization of the United Nations (FAO), for Denmark	2013	Bruno et al. (2019)
France	4	2978	Survey data from the Nutritional Behaviour and Food Consumption in France	2010	Coelho et al. (2016)
Portugal	2	NA[a]	Portuguese food balance sheets and surveys conducted by the Portuguese National Institute of Statistics	2008–2016	Esteve-Llorens et al. (a) Esteve-Llorens et al. (2020)
Spain	2	NA[a]	A weekly diet based on the energy needs of an active Spanish adult woman according to the Food and Agriculture Organization of the United Nations (FAO)	2014	Esteve-Llorens et al. (b) Esteve-Llorens et al. (2019)
USA	2	NA[a]	United States Department of Agriculture (USDA) Dietary Guidelines and the Harvard University Healthy Eating Plate	2010	Gephart et al. (2016)
Spain	3	NA[a]	Dietary patterns promoted by public health agencies, foundations, and the Spanish Ministry of Health and Consumer Affairs and Social Welfare	2019	Gonzalez-Garcia et al. (2020)
USA	3	9762	National Health and Nutrition Examination Survey (NHANES) and diets that meet the Dietary Guidelines for Americans (DGA)	2007–2008	Hitaj et al. (2019)
Netherlands	3	2102	Dutch National Food Consumption Survey	2007–2010	Seves et al. (2017)
Denmark	3	1385	Danish National Survey of Dietary Habits and Physical Activity (DANSDA), based on seven-day diet records	2005–2008	Mertens et al. (2020)
Czech Republic	3	1386	Czech National Food Consumption Survey (SISP04), based on two 24-h recalls spaced over three to five months	2003–2004	
Italy	3	1978	Italian National Food Consumption Survey (INRAN-SCAI), based on three day–day diet records	2005–2006	
France	3	1713	Second French Individual and National Study on Food Consumption cross-sectional dietary survey (INCA2)	2006–2007	
Denmark	5	2025	Danish National Survey on Dietary Habits and Physical Activity	2005–2008	Mogensen et al. (2020)
Italy	4	NA[a]	Guidelines defined by the Italian Nutrition Society (SINU) and the daily recommended intake of nutrients (LARN)	2010	Pairotti et al. (2015)
France	2	1899	Second French Individual and National Study on Food Consumption cross-sectional dietary survey (INCA2)	2006–2007	Perignon et al. (2017)
Finland	4	NA[a]	Balance Sheets for Food Commodities (2006) and the Yearbook of Farm Statistics (2007) from the Information Centre of the Finnish Ministry of Agriculture and Forestry	2006, 2007	Risku-Norja et al. (2008)
Sweden	3	2140	Riksmaten Adults food intake survey	2010–2011	Karlsson Potter and Röös (2021)
Italy	3	153	Food and beverage recall over a seven-day period by the Department of Food Science of the University of Parma	2014	Rosi et al. (2017)
UK	7	55,504	Semi-quantitative food-frequency questionnaire (FFQ) from participants in the Oxford component of the European Prospective Investigation into Cancer and Nutrition (EPIC-Oxford) cohort	1993–1999	Scarborough et al. (2014)
Canada	7	10,723	Canadian Community Health Survey 2.2 (CCHS)	2004	Veeramani et al. (2017)

[a] Denotes not applicable as the study was based on Food Balance Sheets or nationally recommended diets.

Table 3
Pooled key descriptive characteristics of identified farm-to-fork studies.

Characteristics	Study N (%)[a]	Characteristics	Study N (%)[a]
Publication year (n = 26)		**No. of dietary records identified (n = 99)**	
2009	1 (3.8)	High-protein diet	8 (8.1)
2014	3 (11.5)	Lacto-ovo-vegetarian/pescatarian	20 (20.2)
2015	1 (3.8)	Omnivorous diet	28 (28.3)
2016	3 (11.5)	Recommended diet	35 (35.4)
2017	3 (11.5)	Vegan	8 (8.1)
2018	4 (15.4)		
2019	2 (7.7)	**No. of dietary records with reported GHG emissions**	
2020	9 (34.6)	High-protein diet	8/8 (100)
		Lacto-ovo-vegetarian/pescatarian	20/20 (100)
Original diet study year (n = 26)		Omnivorous diet	28/28 (100)
1990–2000	3 (11.5)	Recommended diet	35/35 (100)
2001–2010	15 (57.7)	Vegan	8/8 (100)
2011–2020	8 (30.8)		
		No. of dietary records with reported kcal consumption	
Country of study (n = 26)		High-protein diet	8/8 (100)
Canada	1 (3.8)	Lacto-ovo-vegetarian/pescatarian	19/20 (95)
Czech Republic	1 (3.8)	Omnivorous diet	26/28 (92.9)
Denmark	3 (11.5)	Recommended diet	31/35 (88.6)
Finland	1 (3.8)	Vegan	8/8 (100)
France	4 (15.4)		
Italy	3 (11.5)	**No. of dietary records with reported GHG emissions by region (n = 99)**	
Portugal	1 (3.8)	Eastern Europe	3 (3.0)
Spain	4 (15.4)	Northern Europe	28 (28.3)
Sweden	1 (3.8)	Southern Europe	26 (26.3)
The Netherlands	4 (15.4)	Western Europe	30 (30.3)
UK	1 (3.8)	North America	12 (12.1)
USA	2 (7.7)		
		No. of dietary records with reported kcal consumption by region (n = 92)	
Continent of study (n = 26)		Eastern Europe	3 (3.3)
North America	3 (11.5)	Northern Europe	28 (30.4)
Europe	23 (88.5)	Southern Europe	22 (23.9)
		Western Europe	27 (29.3)
No. of studies per region (n = 26)		North America	12 (13.0)
North America	2 (7.7)		
Eastern Europe	21 (80.8)	**Study population (n = 26)**	
Northern Europe	18 (69.2)	Study Population Reported	18 (69.2)
Southern Europe	20 (76.9)	Total reported population	177,736
Western Europe	9 (34.6)		

[a] Percentage of the extracted variable of interest based on the total number of articles (n).

Table 4
Post Hoc Tukey's HSD test for multiple comparisons of the lacto-ovo-vegetarian/pescatarian dietary pattern's daily kcal consumption across five geographic regions.

	E. Europe	N. Europe	S. Europe	W. Europe	N. America
Eastern Europe	–	+6.9% (0.368)	−1.3% (0.996)	−3.4% (0.859)	−0.8% (≈1.000)
Northern Europe		–	−8.2% (0.084)	−10.3% (0.014) *	−7.6% (0.169)
Southern Europe			–	−2.1% (0.941)	+0.6% (≈1.000)
Western Europe				–	+2.7% (0.902)
North America					–

Mean differences are shown, and the p-value in parentheses.
* Denotes the mean differences that are significant at 0.05 level

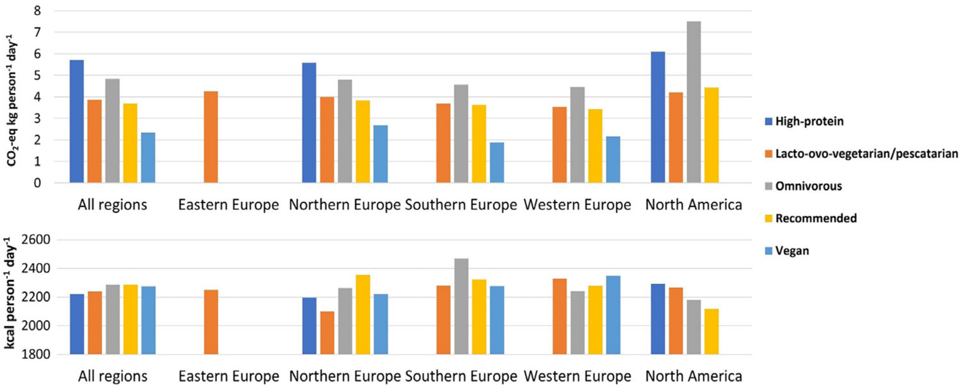

Fig. 2. Regionally delineated GHG emissions (CO_2eq kg person^{-1} day^{-1}) and kcal consumption (kcal person^{-1} day^{-1}) for each dietary pattern.

Table 5
Statistical summary of five identified dietary patterns (high-protein, lacto-ovo-vegetarian/pescatarian, omnivorous, recommended, and vegan) delineated by region; 99 GHG emissions (CO_2eq kg person^{-1} day^{-1}) and 92 kcal consumption (kcal person^{-1} day^{-1}) data records are included. Regions were based on the United Nations Statistics Division (UNSD). The mean GHG emissions for diets with a standardised daily 2000 kcal consumption are included.

Dietary pattern	Descriptive statistics	Eastern Europe[b]		Northern Europe[c]		Southern Europe[d]		Western Europe[e]		North America[f]		Total	
		CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}	CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}	CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}	CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}	CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}	CO_2eq kg person^{-1} day^{-1}	kcal person^{-1} day^{-1}
High-protein	No. of studies	–	–	6	6	–	–	–	–	2	2	8	8
	Mean (SD[a])	–	–	5.59 (1.07)	2198 (217)	–	–	–	–	6.10 (3.63)	2294 (NC[g])	5.71 (1.66)	2222 (189)
	SM[h] (SD[a])	–	–	5.16 (1.28)	–	–	–	–	–	5.32 (3.16)	–	5.20 (1.61)	–
	Min/Max	–	–	4.2/7.19	2000/2413	–	–	–	–	3.53/8.66	2294	3.53/8.66	2000/2413
	Test statistic[i]											0.738	0.576
Lacto-ovo-vegetarian/ pescatarian	No. of studies	2	2	5	5	5	4	5	5	3	3	20	19
	Mean (SD[a])	4.25 (0.67)	2250 (NC[g])	3.99 (0.44)	2100 (137)	3.68 (0.97)	2280 (76)	3.53 (1.49)	2328 (86)	4.21 (1.60)	2267 (46)	3.86 (1.04)	2240 (123)
	SM[h] (SD[a])	3.78 (0.60)	–	3.80 (0.34)	–	3.00 (0.82)	–	3.08 (1.38)	–	3.74 (1.50)	–	3.43 (0.99)	–
	Min/Max	3.77/4.72	2250	3.71/4.76	2000/2250	2.6/4.78	2228/2393	2.04/5.48	2250/2420	2.78/5.94	2214/2294	2.04/5.94	2000/2420
	Test statistic[i]											0.884	0.022*
Omnivorous	No. of studies	1	1	8	8	6	5	11	10	2	2	28	26
	Mean (SD[a])	–	–	4.80 (0.63)	2263 (246)	4.56 (0.69)	2470 (322)	4.45 (0.85)	2241 (156)	7.50 (1.76)	2182 (158)	4.83 (1.09)	2288 (228)
	SM[h] (SD[a])	–	–	4.28 (0.73)	–	3.58 (0.71)	–	4.04 (0.77)	–	6.95 (2.12)	–	4.29 (1.16)	–
	Min/Max	–	–	3.97/5.66	2000/2666	3.84/5.6	2228/3017	3.65/6.23	1910/2420	6.25/8.74	2070/2294	3.65/8.74	1910/3017
	Test statistic[i]											0.001*	0.273
Recommended	No. of studies	–	–	6	6	13	11	12	10	4	4	35	31
	Mean (SD[a])	–	–	3.83 (0.66)	2356 (300)	3.63 (0.86)	2323 (216)	3.42 (0.96)	2279 (154)	4.43 (1.86)	2119 (145)	3.68 (1.01)	2287 (212)
	SM[h] (SD[a])	–	–	3.30 (0.77)	–	2.87 (0.39)	–	3.01 (1.04)	–	4.18 (1.72)	–	3.17 (0.97)	–
	Min/Max	–	–	2.85/4.67	2000/2666	2.79/5.47	2100/2764	2.04/4.95	1903/2420	2.59/6.81	2000/2294	2.04/6.81	1903/2764
	Test statistic[i]											0.386	0.336
Vegan	No. of studies	–	–	3	3	2	2	2	2	1	1	8	8
	Mean (SD[a])	–	–	2.68 (0.23)	2222 (385)	1.88 (0.66)	2277 (69)	2.16 (0.17)	2351 (98)	–	–	2.34 (0.46)	2276 (217)
	SM[h] (SD[a])	–	–	2.46 (0.43)	–	1.64 (0.52)	–	1.85 (0.22)	–	–	–	2.08 (0.49)	–
	Min/Max	–	–	2.44/2.89	2000/2666	1.41/2.34	2228/2326	2.04/2.28	2281/2420	–	–	1.41/2.81	2000/2666
	Test statistic[i]											0.163	0.883

* Denotes the mean differences that are significant at 0.05 level.

[a] Standard deviation.

[b] Czech Republic.

[c] Denmark, Finland, Sweden, and the United Kingdom.

[d] Italy, Portugal, and Spain.

[e] France and the Netherlands.

[f] Canada and the United States of America.

[g] Not calculated.

[h] Standardised GHG emission mean to 2000 kcal consumption per day.

[i] Test statistic for non-standardised mean.

Table 6
Post Hoc Tukey's HSD test for multiple comparisons for (i) five dietary pattern's GHG emissions across all regions and percent differences and (ii) the omnivorous dietary pattern's GHG emissions across four geographic regions.

(i)	Omni	Rec	VE-Pes	HP	VG
Omni	–	+27% (0.001) *	+22% (0.021) *	−17% (0.253)	+69% (<0.001) *
Rec		–	−5% (0.978)	−43% (<0.001) *	+45% (0.016) *
VE-Pes			–	−39% (0.001) *	+49% (0.009) *
HP				–	+84% (<0.001) *
VG					–
(ii)		**N. Europe**	**S. Europe**	**W. Europe**	**N. America**
Northern Europe		–	+5% (0.949)	+8% (0.804)	−44% (0.002) *
Southern Europe			–	−2% (0.994)	−49% (0.001) *
Western Europe				–	−51% (<0.001) *
North America					–

Post Hoc comparison using Tukey's HSD. Mean differences are shown, and the p-value in parentheses.
* Denotes the mean differences that are significant at 0.05 level.
** Eastern Europe not included as there was only one record.

regions and North America, with North America exhibiting a significantly higher mean value (7.50 CO_2eq kg person^{-1} day^{-1}), compared to mean calculated emissions for the European regions of 4.80 (−44%), 4.56 (−49%), and 4.45 (−51%) CO_2eq kg person^{-1} day^{-1} for Northern, Southern, and Western Europe, respectively (Table 6).

3.4. *Standardised dietary patterns and GHG emissions*

As shown (Table 5), standardised mean GHG emissions were typically lower than the pre-standardised mean as the reported kcal consumption in the identified literature was typically (90/92; 98%) > 2000 kcal per day. The study by Biesbroek et al. (2018) contained the only dietary records where kcal consumption occurred below 2000 kcal person^{-1} day^{-1}, a recommended diet and omnivorous diet equating to 1903 and 1910 kcal person^{-1} day^{-1}, respectively. The least significant change was the high-protein diet, while the recommended diet had the most significant pre- and post-standardisation difference. The three remaining dietary patterns reported an analogous decrease in their mean GHG emissions. As for the regional breakdown, the mean GHG emissions for the lacto-ovo-vegetarian/pescatarian diet in Northern Europe had the least significant change, while the omnivorous diet in Southern Europe had the most significant change.

A statistically significant difference was found between standardised mean dietary GHG emissions and the five extracted dietary scenarios ($F(4) = 14.386$, $p < 0.001$) (Table 7). When comparing significant statistical differences between the pre- and post-standardisations results, the vegan dietary pattern was no longer significantly less than the recommended dietary pattern, with the percentage difference in

Table 7
Post Hoc Tukey's HSD test of multiple comparisons for (i) five dietary pattern's GHG emissions across all regions and (ii) the omnivorous dietary pattern's GHG emissions across four geographic regions with percentage differences between the dietary patterns when daily kcal consumption was standardised to 2000 kcal per day.

(i)	Omni	Rec	VE-Pes	HP	VG
Omni	–	+27 → +30% (0.001) *	+22 → +22% (0.069)	−17 → −19% (0.225)	+69 → +69% (<0.001) *
Rec		–	−5 → −8% (0.915)	−43 → −49% (<0.001) *	+45 → +42% (0.085)
VE-Pes			–	−39 → −41% (0.002) *	+49 → +49% (0.028) *
HP				–	+84 → +86% (<0.001) *
VG					–
(ii)		**N. Europe**	**S. Europe**	**W. Europe**	**N. America**
Northern Europe		–	+5% → +18% (0.469)	+8% → +6% (0.934)	−44% → −48% (0.004) *
Southern Europe			–	−2% → −12% (0.764)	−49% → −64% (0.001) *
Western Europe				–	−51% → −53% (0.001) *
North America					–

Post Hoc comparison using Tukey's HSD. Pre- and post-standardised mean differences are shown on the left and right sides of the arrow, respectively, and the p-value in parentheses.
* Denotes the mean differences that are significant at 0.05 level.

emissions decreasing from 45% to 42% but remaining statistically significant at $\alpha = 0.1$. Likewise, the lacto-ovo-vegetarian/pescatarian diet was no longer associated with significantly lower GHG emissions compared to the omnivorous diet with a 22% difference in mean GHG emissions; however, the difference remained significant at $\alpha = 0.1$. After standardisation, the percent difference in GHG emissions between the high-protein diet and the other diets all increased, ranging from two percentage points for the omnivorous, lacto-ovo-vegetarian/pescatarian, and vegan dietary patterns to six percentage points for the recommended dietary pattern.

As for regional differences, similar to the pre-standardised daily kcal consumption results, significant statistical differences were only reported for the omnivorous diet (F(3) = 7.786, $p = 0.001$) between North America and the European regions (Table 7). North America retained a significantly higher mean standardised GHG emission of 6.65 CO_2eq kg person^{-1} day^{-1} while the European regions were associated with mean standardised GHG emissions of 4.28 (−48%), 4.04 (−53%), and 3.58 (−64%) CO_2eq kg person^{-1} day^{-1} for Northern, Western, and Southern Europe, respectively.

4. Discussion

To the author's knowledge, the current study represents the first to pool and analyse reported farm-to-fork GHG emissions of five distinct dietary patterns across high-income countries. Study findings based on international peer-reviewed literature show that dietary patterns and geographic regions undoubtedly directly relate to climate change via GHG emissions.

4.1. Regional GHG emission differences

Based on the included studies, there were significant differences in mean dietary GHG emissions between the European regions and North America for the same type of identified dietary patterns pre- and post-daily consumption standardisation. This finding may be attributable to several factors, for example, EU agriculture is the only major food system in the world that successfully reduced GHG emissions (reduced by 20% since 1990) (EC, 2020). Additionally, differences in European and North American geography, food availability, consumption habits, food prices, and food production methods also likely impact the differing GHG emissions (Goldstein et al., 2017; Mitchell, 2004; Normile and Leetmaa, 2004). It is also known that within a dietary LCA the majority of agricultural related emissions arise during the production stage; therefore, the different agricultural production and processing methods between North America and Europe also impact the magnitude of GHG emissions from food production (Corrado et al., 2019; Kim et al., 2020; Lacour et al., 2018).

4.2. Dietary GHG emission reduction potential

The findings present an undoubted potential for significantly reducing GHG emissions between food production and consumption through the change of dietary patterns in high-income regions which would be beneficial for the climate. The GHG reduction potential is primarily depending on the type and quantity of meat and animal products being consumed (Hendrie et al., 2016; Mertens et al., 2020; Ridoutt et al., 2021; Scarborough et al., 2014; Seves et al., 2017). Within the current study, omnivorous diets and high meat consumption were associated with significantly higher GHG emissions than diets with less meat consumption, including the recommended, vegetarian, and vegan dietary patterns.

The percentage of GHG reductions resulting from a dietary change within identified studies is similar to previously published systematic review papers by Aleksandrowicz et al. (2016) and Hallstrom et al. (2015). However, differences were found in the percentage of GHG reduction potential from switching dietary patterns. Switching to a vegan dietary pattern from an "average diet" or omnivorous diet has the potential to reduce GHG emissions by 35%–53% and 23%–53%, as reported by Aleksandrowicz et al. (2016) and Hallstrom et al. (2015), respectively. Comparatively, within the scope of high-income regions, our pooled analysis indicates a ≈69% potential reduction in GHG emissions via switching from an omnivorous diet to a vegan diet. By switching to vegetarian and pescatarian dietary patterns, GHG emissions were reduced by around 23%–38% (Aleksandrowicz et al., 2016) and 18%–35% (Hallstrom et al., 2015). These reductions were similar to the 22% potential GHG reductions reported in the current study. Aleksandrowicz et al. (2016) reported a "healthy guidelines + further optimisation" dietary pattern equivalent to a 20%–35% reduction of GHG emissions, while Hallstrom et al. (2015) reported GHG reductions for a "ruminant meat replaced by pork and poultry" diet of approximately 18%–33%. These developed hypothetical dietary patterns are both equivalent to the identified recommended diet, which was calculated to result in a 30% GHG emissions decrease compared to the omnivorous dietary pattern. These differences might be attributed to the scope of the studies, as Aleksandrowicz et al. (2016) and Hallstrom et al. (2015) employed a global scope, included grey literature, and utilised differing definitions for identified dietary patterns. The per capita GHG emissions of the five dietary patterns covered in this study were also comparable to the equivalent dietary emissions reported in the study by Scarborough et al. (2014), which examined dietary emissions from the United Kingdom. Reducing GHG emissions is essential for agricultural systems as agricultural systems depend on stable climatic conditions (Campbell et al., 2016). Therefore, shifting from high GHG emitting dietary patterns to more sustainable ones will not only aid in slowing down climate change but will also ensure future food security.

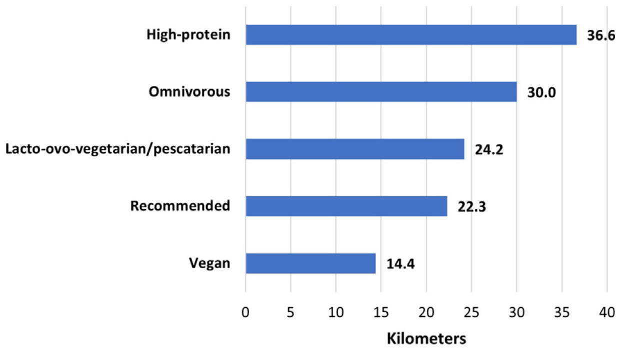

Fig. 3. Bar chart summarising the equivalent distance needed to drive every day for a year to equal the GHG emissions for the corresponding dietary pattern.

To consider the mean GHG emissions values for high-income countries from farm-to-fork activities for each of the five identified dietary patterns, a motor vehicle analogy was utilised to compare dietary GHG emissions standardised to 2000 kcal per day and the equivalent driving distance. Based on the Worldwide Harmonised Light-Duty Vehicles Test Procedure, the European Environmental Agency (EEA) reports that an average car in 2020 with an engine capacity of 1396 cm^3 and engine power of 95 kW emits approximately 0.1419 kg CO_2 km^{-1} (EEA, 2020); accordingly, annual dietary emissions were calculated and the equivalent distance needed to drive every day for a year are shown in Fig. 3.

- **High-protein diet:** 1.90 Mt CO_2eq $person^{-1}$ yr^{-1}
- **Lacto-ovo-vegetarian/pescatarian diet:** 1.25 Mt CO_2eq $person^{-1}$ yr^{-1}
- **Omnivorous diet:** 1.57 Mt CO_2eq $person^{-1}$ yr^{-1}
- **Recommended diet:** 1.16 Mt CO_2eq $person^{-1}$ yr^{-1}
- **Vegan diet:** 0.75 Mt CO_2eq $person^{-1}$ yr^{-1}

4.3. Reducing dietary GHG emissions through dietary change and policy measures

Based on the studies included in this review, where the mean emissions for the standardised omnivorous and recommended dietary patterns for Western Europe were found to be 4.04 CO_2eq kg $person^{-1}$ day^{-1} and 3.01 CO_2eq kg $person^{-1}$ day^{-1}, respectively, the potential emission reductions resulting from a dietary shift can be calculated. Western Europe, as defined by the United Nations Statistics Division, has a population of 196 million people, and if the entirety of Western Europe were to switch from an omnivorous diet to a recommended diet, farm-to-fork emissions would be reduced by 25.6%. This reduction would help meet the goal set by the European Commission to reduce domestic GHG emissions in the European Union to at least 40% below 1990 levels and the reduction of GHG emission would carry additional climatic benefits (Seves et al., 2017). This dietary shift could be supported by promoting the various recommended diets, such as diets based on healthy eating guidelines, Mediterranean and Atlantic diets, diets incorporating partial meat substitution by plant-based products, and diets with decreased meat and dairy consumption (Bassi et al., 2022; Castaldi et al., 2022; Gibbs and Cappuccio, 2022). In addition, improved farming practices can also be implemented, as Chiriacò et al. has described, organic food polices can aid in the transition to sustainable diets while significantly contributing to GHG reduction (Chiriacò et al., 2022). However, target groups (i.e., frequent meat eaters) need to be identified which may be undertaken by examining relationships between dietary patterns and socio-economic status and health within specified populations (Ax et al., 2016; Farchi et al., 2017; Kim et al., 2020).

Once target groups have been identified, environmentally friendly diets can be promoted through public and private sectors by improving education and labelling to empower consumers to choose more sustainable dietary options and allow them to be aware of the impact of their choices. Tax incentives might also be used to drive the transition to a sustainable, more environmentally friendly food system with less impact on climate change. The uptake of these diets can offer a route to achieving international goals such as the Paris Climate Change Agreement and the Sustainable Development Goals (i.e., Climate Action, Life on Land, Partnerships to achieve the Goal) as well as regional goals such as the European Green Deal's Farm to Fork Strategy, all of which aim to reduce agricultural GHG emissions through shifting dietary patterns (EC, 2020; FAO, 2018).

Examining the environmental impacts of different dietary patterns from a farm-to-fork perspective is required to raise awareness among policymakers and individual consumers (Chaudhary and Tremorin, 2020; Grosso et al., 2020). Accordingly, evidence-based environmentally friendly and healthy diets can be developed and implemented, catalysing a global diet transformation shift to mitigate GHG emissions from anthropogenic agricultural activities and help limit global warming to less than 2 °C thus decelerating anthropogenic climate change (Chaudhary and Tremorin, 2020; Grosso et al., 2020). Domestic behaviours (i.e., food purchasing patterns, cooking methods, and food waste) may play a large role in this dietary shift and needs to be examined in more detail (Corrado et al., 2019; Wang et al., 2021). Food production systems reflect current dietary patterns and play a significant role in dietary GHG emissions, especially in terms of food loss and waste since it occurs in all stages of the food supply chain, and therefore need improved communication in the supply chain and promote circular economies (Corrado et al., 2019; Wang et al., 2021).

5. Conclusions, limitations, and future research

The current study sought to examine five pre-defined dietary patterns within high-income countries in Europe and North America and statistically characterise their environmental impacts using calculated GHG emissions as the primary environmental indicator. Study findings suggest that by shifting from diets associated with high GHG emissions, i.e. high-meat and omnivorous diets, to diets with lower GHG emissions, such as recommended, vegetarian, or vegan diets, GHG emissions from the farm-to-fork boundary have the potential to be reduced by up to 86% in Europe and North America. The omnivorous dietary pattern in North America had significantly higher GHG emissions than the equivalent dietary pattern in Europe. Study findings will assist policy makers and individual consumers transition from high GHG diets patterns to increasingly sustainable consumption patterns, thus aiding climate change mitigation and planetary health.

Limitations associated with the current study mirror those of many scoping reviews with diverse definitions, terminology, a regional paucity of literature, limited number of articles, and a lack of standardised methodologies, especially with dietary LCAs, however, these limitations can partially be explained by the novelty of the research field and highly focused inclusion criteria (Grosso et al., 2020; Vieux et al., 2020). Study results may only be generalisable across high-income countries in Europe and North America as that was the current scope for the study, thus the authors advise that caution be employed when investigating dietary emissions in low- and middle-income countries and high-income countries outside of Europe and North America. Furthermore, this study only examined the environmental impact of dietary patterns with respect to GHG emissions, and acknowledge that several other environmental impact categories could be considered, including but not limited to water use, eutrophication, acidification and loss of biodiversity (Rockström et al., 2009; Röös et al., 2013; van Dooren et al., 2014). Agricultural and food life cycles are complex, and the by-products or waste produced during the various stages of the life cycle may become a new resource in other industrial and economic sectors (Caffrey and Veal, 2013; Wang et al., 2021). This may lead to a lack of accuracy as the by-products may not be quantified and included, for example, livestock manure being used for fertiliser, compost, and heat and power generation, thus more research should be done on these life-cycle by-products (Awasthi et al., 2022). Additionally, due to individual, economic, regional, and social–cultural diversity, dietary patterns are rarely nationally and regionally identical, while shifting population profiles will also impact GHG emissions (Aleksandrowicz et al., 2016; Horgan et al., 2016; Vieux et al., 2020). Limitations may also be related to the time period of the dietary studies used in the various analyses and a degree of caution should be employed as dietary patterns will and have undoubtedly changed over time.

Future research relating to holistically assessing the environmental impact of dietary patterns, and particularly GHG emissions, is necessary. Human behaviours and consumption patterns within and across different populations and geographical locations significantly impact dietary choices, therefore, the sociodemographic variables impacting these choices should be expanded on in future studies. In addition to GHG emissions, several environmental indicators require further examination to aid identification of dietary patterns that are increasingly sustainable and healthy to aid compliance with the SDGs put forth by the UN.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2023.100108.

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