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The relationship between dietary greenhouse gas emissions and demographic characteristics in high-income countries

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Abstract

The food we eat has a critical impact on human and planetary health. Food systems are responsible for approximately a third of total global greenhouse gas emissions (GHGEs). This review summarises studies that have measured dietary GHGEs and assessed their associations with various demographic variables. Most studies report dietary emissions at the individual level, but some studies use households as the unit of analysis. Studies investigating individuals estimate dietary intakes using 24-hour dietary recalls, food frequency questionnaires, diet history interviews, food diaries or other dietary records. Studies investigating households rely on food purchasing data and expenditure surveys. The majority of studies estimate dietary GHGEs using process-based life cycle assessments. It is difficult to directly compare emissions estimates between studies at either the individual or household-level due to methodological differences. In general, there are mixed findings with regards to the relationships between various demographic variables and dietary emissions, although older adults generally had higher dietary GHGEs than younger adults, and men typically had higher dietary GHGEs than women, even when standardizing for total energy intake. This review may be useful in informing and targeting policies and interventions to reduce GHGEs of dietary intake.

Keywords: diets; greenhouse gas emissions; life cycle assessment; demographic variables

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Introduction

In 2019, nearly 8 million deaths were attributable to dietary risk factors including low intake of fruit and vegetables, whole grains, legumes, and nuts and seeds, and high intakes of red meat and processed meats [1]. In addition to health impacts, the production of food along with the associated transport, storage, cooking, and wastage produce substantial amounts of greenhouse gas emissions; taking these various life stages into consideration, food systems are estimated to account for between a quarter to a third of total global greenhouse gas emissions (GHGEs) [2,3]. These GHGEs include methane (a by-product of the digestion of plant matter in ruminant livestock), carbon dioxide (from fossil fuels used to power farm machinery and to transport, store, and cook foods), and nitrous oxide (from nitrogen fertilisers and the urine of grazing livestock) [3]. For further details on the methods most commonly used to measure GHGEs arising from the production, distribution, and storage of food, see section titled, 'Environmental Impact Assessments'.

Generally, the production of animal-sourced foods results in greater amounts of GHGEs compared to plant-sourced food products (by weight) [4], and a previous study estimated that the GHGEs associated with meat eaters' diets are approximately twice as high as those of vegans [5]. Thus, dietary changes could reduce GHGE, and Hallström et al. (2015) estimated that dietary shifts only within affluent countries could result in a 50% reduction in global food-related GHGEs [4]. The EAT-Lancet Commission proposes a healthy diet predominantly consisting of fruits, vegetables, whole grains, legumes and nuts and unsaturated oils, with modest amounts of seafood and poultry and low amounts of red meat, added sugar, refined grains and starchy vegetables [6]. This diet was designed to provide healthy nutrition for an estimated global population of roughly 10 billion people by 2050 while keeping the global food system within planetary boundaries [6].

To facilitate global shifts towards diets that are both sustainable and healthy, understanding the relationship between demographic characteristics and the environmental impact of diets is important. Many modelling studies have been carried out to estimate theoretical benefits (both in terms of impacts on health and the environment) from population shifts from a diet with relatively high amounts of animal-source food to a diet lower in animal-source foods [7,8]. This review summarises studies carried out in high-income countries that have estimated GHGEs from self-selected diets in free-living people (at an individual or household level) and considers associations with various demographic variables such as age, gender or sex, income level, and education level. As such, the review focuses on studies undertaken in high-income countries with relatively westernized diets such as the US, European countries, Canada, Australia and New Zealand.

General characteristics of studies examining the relationships between demographic characteristics and dietary GHGEs

Studies that have investigated the associations between demographic characteristics and dietary GHGEs are summarised in Table 1. Studies either investigate individuals or households as the sampling unit; or occasionally studies collect data on both individuals and households [9]. Research in this area has been conducted in various high-income countries within Europe, for example in Sweden [10–12], Denmark [9,13], Germany [14,15], Ireland [16,17], the United Kingdom [18,19], the Czech Republic [13], Finland [20], France [13], Italy [13], the Netherlands [21], and Switzerland [22]. Outside of Europe, some studies have been conducted in the United States [23,24], Australia [25], and New Zealand [26].

Studies examining the possible associations between dietary GHGEs and demographic variables have used observational, cross-sectional research designs [9–26]. In order to estimate participants' dietary GHGEs, each study collected food consumption or purchasing data for its sample and then assigned emissions values to the food products before comparing total dietary GHGEs by various demographic variables. For each of these steps, researchers have used a variety of methods and data sources which are described in detail below.

Food purchasing and consumption data

Studies that have estimated dietary GHGEs have either used food purchasing data of households [9,10,18,20,23,25,26] or food consumption data of individuals [9,11–17,19,21,22,24] or occasionally collected food consumption data for both households and individuals within each household in order to corroborate the accuracy of both sets of data [9].

For households, some studies used food purchasing data recorded by participants [9,18,23,26], measured over a single 7-day period [23], a single 14-day period [18], or an entire year [9,26]. Others have used data collected from expenditure surveys [10,20,25], measuring household spending over the course of a week [25] or an entire year [10]. Regarding studies that assessed individuals' food intake, methods of data collection include a single 24-hour dietary recall [24] or multiple 24-hour dietary recalls [13,14,21,22]; food diaries and other forms of dietary records generated over the course of three [13], four [16,17], or seven consecutive days [13]; food frequency questionnaires (FFQs) [9,11,12,15]; and dietary history interviews [14].

Accurately identifying usual food purchases for a household or food consumption for an individual is challenging, and all of the aforementioned methods of collecting usual dietary data have well-known limitations. In studies using food purchasing data, the failure of participants to reliably or correctly record every purchase may introduce measurement error. For example, nonresponses and underreporting of food acquisitions have been found to increase as the time period of data collection increases [27]. In addition, not all food purchases may be included in studies; for example, some studies may not capture foods purchased and consumed away from the home (e.g., at restaurants and cafes) [26]. Furthermore, studies using household expenditure data may be susceptible to measurement errors depending on the extent to which they rely on individuals' estimates and are not corroborated with actual purchasing records [28]. In studies using self-reported dietary intake, under-reporting is typical [29], most likely due to a combination of factors such as recall error and social-desirability bias. One study in this field minimized this risk by combining multiple types of consumption data to validate self-reported dietary intake [9].

Environmental impact assessments

Process-based LCAs

To measure the GHGEs resulting from households' and individuals dietary consumption, studies primarily employ the process-based life cycle assessment (LCA) methodology. Process-based LCAs constitute a 'bottom up' approach to quantifying GHGEs, compiling estimates for the emissions incurred both directly and indirectly (also known as 'embodied emissions') at each individual step in a food's life cycle within a given country or region. This method can be applied to all stages of a food's life cycle—agricultural production, processing, packaging, transport, storage, preparation, and waste—and requires thorough analysis of the materials and resources expended (inputs) as well as the emissions and wastes (outputs) generated. For example, to quantify the GHGEs generated from dairy production, a process-based LCA approach considers the nitrous oxide emitted in the production of nitrogen fertilizers for livestock feed in addition to the methane produced by cattle, the nitrous oxide released in cattle urine, and the carbon dioxide emitted in the transport of the dairy outputs [30]. Process-based LCAs typically express greenhouse gas emissions over a 100-year time horizon, in terms of carbon dioxide equivalents (kgCO_2-e).

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According to the most recent guidance from the Intergovernmental Panel for Climate Change (IPCC), 1 kilogram of carbon dioxide is weighted as 1 $kgCO_2$-e, 1 kilogram of biogenic methane (non-fossil fuel origin, such as from ruminant animals) is weighted as 27 $kgCO_2$-e, and 1 kilogram of nitrous oxide is weighted as 273 $kgCO_2$-e to reflect their respective global warming potential over a 100-year time frame [31].

The accounting of each stage in a food product's life cycle yields comprehensive emissions estimates. However, the considerable level of detail that this "bottom-up" approach requires makes it difficult to undertake. Scientists conducting process-based LCAs must set boundaries for their analyses (i.e., decide which life stages will be included and excluded). Consequently, researchers using LCA data are constrained by the data that is available and relevant to the country where dietary emissions are being examined. As a result, most studies combine numerous LCA datasets in order to expand the scope of the research, and the boundaries of LCA data vary between studies. For example, Rose et al. [24] measured dietary emissions only "from cradle to farm gate" (including only the agricultural production stage) [24] whereas Reynolds et al. [18] incorporated the agricultural and transport stages up to the point of the regional distribution centre (RDC), thus excluding the processing, retail, preparation, and waste stages [18]. Previous research has often used LCAs with the boundaries of "cradle to store" (including agricultural production, processing, transport, and packaging) [14,19,22], "cradle to point-of-sale" (including agricultural production, processing, transport, packaging, and retail overheads) [26], or even "cradle to plate" (including agricultural production, processing, transport, packaging, retail overheads, and preparation) [15–17,21].

Process-based LCAs that do not account for every stage of a food product's life cycle often leave notable gaps in their estimates of foods' emissions, and this is referred to as a truncation error. While the production phase of a food's life cycle generates the largest proportion of GHGEs in the food-system, the other life cycle stages (transportation, processing, packaging, retail, consumption, and waster) also contribute meaningful amounts of GHGEs. Unfortunately, due to insufficient LCA data being available in many instances, it is not always feasible to include all stages of a food product's life cycle within reported LCA data. For example, Crippa et al. [3] estimated that primary production of foods and land use/land-use change emissions account for 39% and 32% respectively (71% total) of total food-system GHGEs in 2015, leaving 29% accounted for by transportation, processing, packaging, retail, consumption, and waste [3].

Furthermore, process-based LCAs are unable to comprehensively account for the complex interdependencies of all products in modern economies. For instance, beyond the emissions generated on farms during food production, one must also consider the emissions generated by the trucks that transport food to retail markets. Food transport trucks not only emit carbon from fossil fuel usage (which many process-based LCAs do account for), they are also made from steel (as well as countless other materials), which requires inputs of energy and material resources and generates outputs in the process of their production. The materials and resources used in the production of steel have their own requisite components—including machines made from more steel, which produces circularity effects—and the analysis can go on indefinitely. Most process-based LCAs do not account for these indirect emissions arising from food production.

Environmentally Extended Input Output (EEIO) modelling

In light of these limitations of the 'bottom-up' process-based LCA methodology, some studies [20,23,25] have instead employed a 'top-down' approach called Environmentally Extended Input Output (EEIO) modelling to quantify the GHGEs generated in the process of producing, distributing, and consuming foods. Economic Input Output (EIO) models are macroeconomic representations of the monetary flows (i.e., transactions) between the various sectors within an economy. Accordingly, they measure what products or services (outputs) are consumed by other industries as inputs, thus quantifying the interdependence of products within complex economies. These datasets are extended into Environmentally-Extended Input Output models by applying emissions 'factors' (i.e., multipliers) to the monetary value of economic activities. Multiplying monetary transaction data by an emissions intensity factor (measured in kilograms of carbon dioxide equivalents (kgCO_2-e) per unit of monetary output) enables researchers to estimate the GHGEs — as well as other environmental costs such as energy and water [25] — associated with a given amount of money spent on a food product [25]. For example, Reynolds et al. (25) took raw spending on various foods and simply multiplied these numbers by assigned values for each food item's GHGEs generated per unit of currency output. EEIO models can also be extended to include international transactions between economies (known as Environmentally Extended Multi-Regional Input-Output, or EE-MRIO, models) to account for the varying inputs and outputs associated with domestic versus imported products [32]. Salo et al. [20] utilised an EEIO model that did not incorporate data on multi-regional inputs and outputs; instead, to estimate the embodied emissions of imported foods, they supplemented their EEIO with LCA data.

Utilizing an EEIO approach in research on dietary emissions helps to minimize truncation error as well as circularity effects. Also known as self-sector transactions, circularity effects refer to when an industry uses its own good as an input to produce more of that good. EEIO models account for this phenomenon, thus enabling comprehensive estimations of climate impacts (both direct and indirect) generated across an entire economy. However, much like with process-based LCAs, the primary strength of EEIO models — their broad scope in linking products within an economy — is also their most significant limitation, as it is dependent upon a high level of aggregation. With regards to food, diverse products with significantly different environmental implications are often combined. For example, Salo et al. [20] used an EEIO approach which grouped all food products into 15 categories [20] whereas Boehm et al. [23] aggregated food products into 26 categories [23]. This level of aggregation does not account for notable differences in GHGEs generated by the distinct food items belonging to the same category. Consequently, it constrains researchers' ability to detect differences in dietary emissions between households or individuals stemming from variations in diet composition or food purchasing, as opposed to the quantity consumed. Therefore, the detail-intensive process-based LCAs are better suited to capture differences between households or individuals in GHGEs resulting from disparate dietary patterns, though they are less effective in accounting for far-reaching indirect and direct environmental impacts of food production across an entire economy.

Finally, for both process-based LCA and EEIO approaches, the standard time frame for quantifying carbon emissions in the reviewed literature was 100-years. Though global warming potential (GWP) can also be measured in a 20-year time frame to better account for greenhouse gases with shorter lifespans (such as methane), or even a 500-year time frame for a longer-term view, the 100-year horizon is most commonly used [33].

Total average household or individual dietary emissions

The lack of methodological uniformity in the literature makes it difficult to compare the studies' findings with regards to averages of total household or individual dietary emissions. Past research has employed differing sampling units, units of measurement, environmental assessment approaches, and boundaries of analysis for such approaches. Even when multiple studies utilize the same sampling unit (i.e., households or individuals) and measurement unit (e.g., kg CO_2 equivalents per person per day), like-for-like comparisons of results derived from process-based LCAs are complicated by important differences in studies' boundaries of analysis. These disparities arise due to the immense challenge of gathering comprehensive, country-specific, and up-to-date emissions data for every stage of a food product's life cycle.

Studies undertaken at the household-level reported their estimates of average dietary emissions GHGEs using various measurement units, including per household per year [for example, 2,290 kgCO_2-e in New Zealand [26], 2,288-kgCO_2-e in Sweden [10], and 3,690 kgCO_2-e in Finland [20]]; per person in a household per year [1,023 kgCO_2-e in New Zealand [26]]; per household per week [80 kgCO_2-e in Australia [25]]; per standard adult equivalent in a given household per week [71.8 kgCO_2-e in the USA [23]]; or per person in a given household per day [2.8 kgCO_2-e in the UK [18]].

Studies undertaken at the individual-level were largely estimated as GHGEs per person averages for women only [2.9 kgCO2-e per person per day in Sweden [11], 3.7 kgCO_2-e per person per day in the Netherlands [21], 5.7 kgCO_2-e per person per day in Germany [15], and 1,533 kgCO_2-e per person per year in Germany [14]]; men only [3.6 kgCO2-e per person per day in Sweden [11], 4.8 kgCO_2-e per person per day in the Netherlands [21], 6.9 kgCO_2-e per person per day in Germany [15], and 2,201 kgCO_2-e per person per year in Germany [14]]; or both men and women [4.3 kgCO_2-e per person per day in Ireland [17], 4.7 kgCO_2-e per person per day in the US [24] and in Sweden [12], 5.2 kgCO_2-e per person per day in Italy [13], 5.4 kgCO_2-e per person per day in Denmark [13], 5.6 kgCO_2-e per person per day in the Czech Republic [13], 6.0 kgCO_2-e per person per day in France [13], 6.5 kgCO_2-e per person per day in Ireland [16], 7.4 kgCO_2-e per day in the UK [19], and 1,200 per person per year in Denmark [9]].

Relationships between demographic variables and dietary emissions

Previous research has examined the relationships between dietary emissions and a variety of demographic variables including income, educational level, age, and sex or gender.

Age

Most studies report a positive relationship between age of the respondent (for studies of individuals) or primary shopper (for studies of households) — or, in the case of Nordström et al. [10], the age of the oldest member of households that do not include any retirees [10]— and

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dietary emissions [10,13,20,24,26]. However, Mertens et al. [13] only observed this association within Denmark and France, and not within the Czech Republic or Italy, where no association was observed [13]. Similarly, Temme et al. [21] found a positive association between age and dietary emissions for girls, boys, and women in the Netherlands, but not for men.

On the other hand, Balter et al. [12] found no significant relationship between the two variables, and several studies found a negative association between age and dietary emissions [11,16,17]. However, one of these studies only observed this negative relationship amongst adults, not children and teenagers [17]. Another study did not adjust for energy intake — the youngest age group (18-35 year olds) had significantly higher dietary emissions than the older age groups, which was attributed to the younger participants' consumption of greater quantities of foods [16].

Gender or sex

The comparison of dietary emissions between men and women can be complicated by greater consumption of quantities of food by men, on average, compared with women. A number of studies have examined differences between genders adjusted for energy intake [13,14,16,24]. Studies that compared dietary GHGEs adjusted by energy intake for men versus women generally found that men's dietary GHGEs were still significantly higher than women's [14,16,24]. These differences are at least partially explained by the fact that men appear to eat more meat than women [14,16]; Meier & Christen [14] found that meat and processed meat products constituted 52% of men's dietary GHGE profiles, compared to 39% for women [14]. Similarly, though differences in meat intake specifically between men and women were not measured by Rose et al. [24], this study from the US found that the highest quintile GHGE diet consisted of a higher proportion of animal protein foods compared to the lowest quintile GHGE diet [24]. Bälter et al. [12] and Kirwan et al. [17] observed the same association between male gender and high dietary GHGEs, though they did not use energy-adjusted dietary GHGEs [12,17]. However, Kirwan et al. [17] did not observe the same association amongst children. Balter et al. [12] also attributed men's higher dietary GHGEs to higher meat intake (as well as higher energy intake overall).

Income level

Findings in the literature in relation to the association between income level and dietary GHGEs are mixed. For example, several studies found a positive relationship between

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household income and dietary emissions [9,10,23], and higher income levels appeared to have higher GHGEs in Australia [25]. In contrast, Boehm et al. [23] found no relationship between participation in SNAP (Supplemental Nutritional Assistance Program) — an indicator of low income — and dietary GHGEs [23], and several other studies have also reported no clear association between income and dietary emissions [17,18,20,22,24,26].

Education level

The literature also reports mixed findings with regards to the association between education level and dietary GHGEs. Several studies found a positive association between the two variables [9,11,23]. Mertens et al. [13] examined data collected in four different European countries; their results showed a positive association between "GHGE density" (referring to energy-standardized dietary emissions) and educational levels in the Czech Republic, a negative correlation in France, and no correlation in Italy or Denmark [13]. Most frequently, though, no clear association was observed between dietary emissions and educational levels [15–17,21,22,24].

Socio-demographic variables

In addition to age, gender, income, and education, previous research has examined the relationship between dietary emissions and various socio-demographic variables. Regarding population density, a study in Sweden found that living in an urban area was strongly associated with higher dietary emissions for individuals [11]. Similarly, Salo et al. [20] observed that households in certain "dense rural" areas of Finland exhibited significantly lower carbon footprints from food consumption compared to the "inner urban" reference group. Studies in Ireland [16] and the Netherlands [21], on the other hand, found no such differences in dietary emissions amongst people living in urban vs. rural areas.

Differences in dietary emissions were also examined between ethnicities in the United States [23,24], as well as between nationalities in Switzerland [22]. The results of studies in the United States indicated that African-American individuals were more likely to consume "low-emitting diets" than individuals of white, Latino, or "other" race-ethnicities [24]; white households were more likely to be in higher dietary GHGE quintiles than black or Asian households [23]; and "non-Hispanic" households were more likely to be in a higher dietary GHGE quintile than Hispanic households [23]. In Switzerland, participants of the

“African/Eastern Mediterranean” nationality had significantly higher dietary GHGEs than the reference group (Swiss) [22].

As for other less commonly examined predictor variables, married participants showed significantly higher dietary GHGEs than divorced participants or those with “other” civil statuses in Switzerland [22]. A study in Sweden observed a relationship between household composition (i.e., the number of adults and children in the household) and dietary emissions such that adults with children accounted for 42% higher dietary emissions than childless adults [10]. In New Zealand, larger households were found to have lower dietary emissions per capita [26].

Environmental Impact Metrics Other Than GHGEs

While the focus of this review was on the relationships between demographic characteristics and dietary GHGEs, the relationships between demographic variables and other environmental indicators have been considered by some researchers: for example, land use (LU) [13,14]; cropland occupation (CLO) [17,22], referring to the use of land suitable for cultivating crops; grassland occupation (GLO) [22], referring to the use of land primarily used for grazing livestock; blue water use, meaning water from surface (e.g., lakes, rivers, reservoirs) and groundwater (e.g., aquifers) sources [14,17], and overall water use [25]; nitrogen and phosphorous use [17]; energy use [25]; and ammonia emissions (measured in grams of ammonia [NH_3] [14]. Findings for each of these will be briefly considered.

Even after adjusting for the weight of foods consumed, men’s diets accounted for 24% higher LU (measured in meters squared per person per year) than women’s diets in Germany [14]; this relationship between gender and land use (as well as ammonia emissions) was caused primarily by higher consumption of meat and lower consumption of fruit and vegetables in men compared with women [14]. Men’s diets were also associated with higher CLO (measured in meters squared) than women’s diets in Ireland [17] and Switzerland [22], as well as higher land use density (m^2/y per kg) in Denmark and the Czech Republic (but not France and Italy) [13]. The same pattern has been observed with blue water use; men’s diets were associated with higher blue water use in Ireland [17].

Regarding age, the diets of older age groups were associated with higher land use in Denmark [13] and Switzerland [22], but not in France, Italy, or the Czech Republic [13]. On the other hand, in Ireland, being younger has been associated with higher CLO (in addition to higher nitrogen and phosphorous use), though older age groups were associated with higher blue water use [17]. Education level has also been positively associated with blue water use in Ireland [17] whereas in Denmark and the Czech Republic, lower educated participants' diets accounted for higher land use densities [13]. In contrast, no association was observed between education level and CLO or GLO for participants' diets in Switzerland, although the highest income group's diets showed higher GLO than the lowest income group's diets [22].

Alignment with Pre-Defined Dietary Patterns

The focus of this review was on studies that had estimated dietary greenhouse gas emissions associated with free living adults consuming self-selected diets. Several studies have also been undertaken that have measured participant alignment to pre-defined dietary patterns and estimated associated dietary greenhouse gas emissions. These studies have generally found that people whose diets more closely align with Mediterranean diet [34,35], a Nordic diet [34], the EAT-Lancet diet [36], or a healthy diet (measured using the Alternate Healthy Eating Index) [34] have relatively lower dietary GHGEs than those whose-consumption patterns align less with the respective diets.

Studies from other countries

This review focused on findings reported in studies undertaken in high-income countries with Western diets; however, several similar studies have been carried out in other countries, including Brazil, Argentina, Mexico, and China. Studies in Brazil [37–39] and China [40] have shown that males have higher dietary GHGEs than females; according to Travassos et al. [39], men's diets had higher water and ecological footprints than women's diets as well [39]. Interestingly, in Mexico, men had higher dietary GHGEs than women without adjusting for energy intake, but women had higher dietary GHGEs per 1000 kcal than men [41].

Two Brazilian studies also showed that the oldest age group [60+ years in one study [39], >65 years in the other [37]] had significantly lower dietary emissions GHGEs than younger adults [18-30, 31-45 and 46-59 years [39]; 45-54 and 55-64 years [37]]; however, as-the results of both these studies were not adjusted for energy intake [37,39] it is possible that these findings could be explained by lower energy intakes in older adults compared with younger adults. Similar results were shown in Mexico, where older adults had lower dietary GHGEs than younger adults without adjusting for energy intake, though adults over 60-years old showed the highest GHGEs per 1000 kcal [41].

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In Mexico, the diets of socially advantaged groups and regions (i.e., those who did not speak an indigenous language, had higher education and socioeconomic status, and lived in an urban environment) accounted for higher GHGEs than socially disadvantaged groups and regions [41]. Similarly, in Brazil, one study found that those with higher family incomes, schooling, or white race had higher dietary GHGEs [38]. Another study in Brazil observed that those with tertiary education had the lowest carbon, water, and ecological footprints compared with those with less education [39]. On the other hand, another Brazilian study found no association between household income and dietary GHGEs [37].

Conclusions

In summary, a range of methodological approaches have been taken to examine dietary GHGEs and their associations with demographic variables. The majority of studies investigate individuals [9,11–17,19,21,22,24] or utilise households as the sampling unit [9,10,18,20,23,25,26]. Studies investigating households estimated household dietary intake primarily using food purchasing data and expenditure surveys. On the other hand, studies of individuals' food consumption relied on 24-hour dietary recalls, food diaries and other dietary records, FFQs, and dietary history interviews. With regards to the calculation of dietary GHGEs, the vast majority of studies employ process-based LCAs [9–19,21–24,26], although a few studies use EEIOs instead [20,23,25]. Total average household or individual emissions are often calculated and reported, yet direct comparisons of these values are hindered by varying sampling units, measurement units, and boundaries of analysis (for those studies which employed process-based LCAs). More often than not, increasing age has been reported as a predictor of higher dietary GHGEs. Male gender has been fairly consistently associated with higher dietary GHGEs, and this trend was evident even in several studies which standardized GHGEs for total energy intake. The relationship between gender and dietary GHGEs appears at least partially mediated by meat intake: several studies found that men eat more meat than women, and another study found that high GHGE diets feature greater proportions of meat than low GHGE diets. A study spanning four countries across Europe (Denmark, Czech Republic, Italy, and France) found that, "intake of energy, total meat, and the proportion of ruminant meat explained most of the variation in GHGE and land use of European diets." [13]

The lack of consistent associations between demographic variables' and dietary GHGEs is perhaps indicative of country-specific mediating factors such as distinctive culinary traditions.

This review provides insights which may be useful in targeting policies and interventions to reduce the GHGEs associated with dietary intake. Considering the sizeable GHGE footprint that human diets have on anthropogenic GHGEs, it is incumbent upon researchers and policy makers to devise interventions to lower dietary GHGEs via population-wide consumption shifts towards lower-emitting, plant-based diets.

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Declaration of Interests

The authors declare none.

Authorship

E Kliejunas: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing**. C. Cleghorn:** Conceptualization, Methodology, Writing - Review & Editing. **J. Drew:** Conceptualization, Methodology, Writing - Review & Editing. **C Ni Mhurchu:** Conceptualization, Methodology, Writing - Review & Editing, Supervision. **K E Bradbury:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

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Table 1: Summary of studies undertaken in high-income countries with relatively westernized diets that consider associations between demographic characteristics and dietary GHGEs.

Reference	Country	Study design, sample size and sampling units	Food consumption data	Method of estimating dietary GHGEs	Boundaries of analysis for process-based LCAs	Total average/median household or individual emissions	Demographic variables examined in relation to dietary GHGEs[1]
Studies of households (in chronological order, most recent to least recent)							
Kliejunas et al., 2023[26]	New Zealand	Cross-sectional; N=1,775 households	Food purchasing Data	Process-based LCA	Cradle to point-of-sale — includes agricultural production, processing, transport/trade, packaging, and retail overheads	1,023 $kgCO_2$-e per capita in a household per year; 2,290 $kgCO_2$-e per household per year (unadjusted geometric mean)	Sex of the primary shopper, household income, age of the primary shopper, household life stage, household size
Salo et al., 2021[20]	Finland	Cross-sectional; N=3,490	Household expenditure	EEIO supplemented	Not applicable	3,690 $kgCO_2$-e per household per year	Income, age, geography

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		households	survey	with LCA inventory data for imported products		(mean)	
Nordström et al., 2020[10]	Sweden	Cross-sectional; N=2,692 households	Household expenditure survey	Process-based LCA	Unknown	2,288 kgCO_2-e per household per year (mean)	Income, age, household composition
Reynolds et al., 2019[18]	United Kingdom	Cross-sectional; N=5,144 households	Food purchasing data	Process-based LCA	Production stage up to the point of the Regional Distribution Centre (RDC) — excludes processing, retail, household use, and waste	2.8 kgCO_2-e per person/day (calculated); household dietary GHGEs were converted to emissions per person in each household based on household composition	Income
Boehm et al., 2018[23]	United States	Cross-sectional; N=4,826 households	Food purchasing data	EEIO	Not applicable	71.8 kgCO_2-e per standard adult equivalent in a given household per week (mean)	Income, educational level, race, ethnicity (race and ethnicity were distinguished as two separate concepts)

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Lund et al., 2017[9]	Denmark	Cross-sectional; N=1,350 households	Food purchasing data for households; Food Frequency Questionnaires for individuals to validate household data	Process-based LCA	Used multiple different LCA datasets whose exact sources and boundaries are unclear	1,200 $kgCO_2$-e per person per year (mean); household emissions were converted to average emissions per person based on household composition	Income, educational level
Reynolds et al., 2015[25]	Australia	Cross-sectional; N=6,957 households	Household expenditure survey	EEIO	Not applicable	80 $kgCO_2$-e per household per week (mean)	Income
Studies of individuals (in chronological order, most recent to least recent)							
Kirwan et al., 2023[17]	Ireland	Cross-sectional; N=2,375 children, N=798 teenagers, and N=4,574 adults	Food Frequency Questionnaires	Process-based LCA	Cradle to plate, or "production until consumption"	4.3 $kgCO_2$-e per adult per day (median); 2.9 $kgCO_2$-e per teenager per day (median);	Age, education status, residential location, sex, social-economic status

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						2.8 $kgCO_2$-e per child per day (median)	
Koelman et al., 2022[15]	Germany	Cross-sectional; N=805 adults	Food Frequency Questionnaires	Process-based LCA	Cradle to plate, or "production to consumption"	6.9 $kgCO_2$-e per man per day; 5.7 $kgCO_2$-e per woman per day	Sex (men vs. women); education status [no training or vocational training (low education) vs. university degree (high education)]; partner status (single vs. married); obesity status (BMI < 30 vs. ≥30 kg/m2)
Frehner et al., 2021[22]	Switzerland	Cross-sectional; N=2,057 adults	Two 24-hour dietary recalls	Process-based LCA	Cradle to store — includes agricultural production, processing, transport/trade, and packaging stages	3.25 $kgCO_2$-e per person per day (median)	Income, educational level, gender

Rippin et al., 2021[19]	UK	Cross-sectional; N=212 adults	Three 24-hour dietary recalls	Process-based LCA	Cradle to store — includes agricultural production, processing, transport/trade, and packaging stages	7.4 $kgCO_2$-e per person per day	Sex, age, obesity status
Mertens et al., 2019[13]	Denmark, Italy, France, and the Czech Republic	Cross-sectional; N=1,739 adults in Denmark; N=1,666 adults in the Czech Republic; N=2,313 adults in Italy; N=2,276 adults in France	Two separate 24-hour dietary recalls in Czech Republic; 7-day diet records in France and Denmark; 3-day diet records in Italy	Process-based LCA	Includes agricultural production, use of primary packaging, transport to retail, food losses and waste, and food preparation; excludes industrial food processing, storage, and transport from retail to home	**Denmark:** 5.4 $kgCO_2$-e per person per day (mean); **Czech Republic:** 5.6 $kgCO_2$-e per person per day (mean); **Italy:** 5.2 $kgCO_2$-e per person per day (mean); **France:** 6.0 kg CO_2-e per person per day (mean)	Educational level, age, gender, BMI
Rose et al., 2019[24]	United States	Cross-sectional; N=16,800 adults	One 24-hour dietary recall	Process-based LCA	Used several different LCA	4.7 $kgCO_2$-e per person per day (mean)	Income, educational level, age, gender,

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					datasets; only the production, and in some cases the processing, stage of foods' life cycles were included; retail, household use, and waste stages were excluded		“race-ethnicity”
Strid et al., 2019[11]	Sweden	Cross-sectional; N=46,893 female adults; N=45,766 male adults	Food Frequency Questionnaires	Process-based LCA	Used numerous different sources with varying boundaries	2.9 $kgCO_2$-e per woman per day (median); 3.6 $kgCO_2$-e per man per day (median)	Educational level, age, geography, BMI
Bälter et al., 2017[12]	Sweden	Cross-sectional; N=5,364 adults	Food Frequency Questionnaires	Process-based LCA	Used multiple different LCA datasets whose exact sources and boundaries are unclear	4.7 $kgCO_2$-e per person per day (median)	Age, gender

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Hyland et al., 2017[16]	Ireland	Cross-sectional; N=1500 adults	Food diaries for four consecutive days	Process-based LCA	"Cradle to plate" — includes agricultural production, processing, transport, and packaging, retail, and preparation stages	6.5 kgCO_2-e per person per day (mean)	Educational level, age, gender, geography
Lund et al., 2017[9]	Denmark	Cross-sectional; N=1,350 households	Food purchasing data for households; Food Frequency Questionnaires for individuals to validate household data	Process-based LCA	Used multiple different LCA datasets whose exact sources and boundaries are unclear	1,200 kgCO_2-e per person per year (mean); household emissions were converted to average individual emissions based on household composition	Income, educational level
Temme et al., 2015[21]	Netherlands	Cross-sectional; N=3,818 children and adults	Two 24-hour dietary recalls	Process-based LCA	Cradle to plate	4.8 kgCO_2-e per man per day; 3.7 kgCO2-e per woman per day; 3.6 kgCO2-e per boy per	Age, education level, physical activity, urbanization grade, BMI, BMR

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						day; 3.2 kgCO2-e per girl per day	
Meier & Christen, 2012[14]	Germany	Cross-sectional; N=13,000 individuals aged 14-80	Multiple 24-hour dietary recalls; dietary history interviews	Process-based LCA	Cradle to store — includes agricultural production, processing, transport/trade, and packaging stages	2,201 kgCO_2-e per man per year (mean); 1,533 kg CO_2 equivalents per woman per year (mean)	Gender

EEIO: Environmentally Extended Input Output [model]; kgCO_2-e: kilograms per carbon dioxide equivalents; LCA: life cycle assessment

[1] Reported demographic characteristics most commonly included age, gender or sex, income level, education level

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