Feature Article

Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets

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The Food and Agriculture Organization defines sustainable diets as nutritionally adequate, safe, healthy, culturally acceptable, economically affordable diets that have little environmental impact. This review summarizes the studies assessing, at the individual level, both the environmental impact and the nutritional quality or healthiness of self-selected diets. Reductions in meat consumption and energy intake were identified as primary factors for reducing diet-related greenhouse gas emissions. The choice of foods to replace meat, however, was crucial, with some isocaloric substitutions possibly increasing total diet greenhouse gas emissions. Moreover, nutritional adequacy was rarely or only partially assessed, thereby compromising the assessment of diet sustainability. Furthermore, high nutritional quality was not necessarily associated with affordability or lower environmental impact. Hence, when identifying sustainable diets, each dimension needs to be assessed by relevant indicators. Finally, some nonvegetarian self-selected diets consumed by a substantial fraction of the population showed good compatibility with the nutritional, environmental, affordability, and acceptability dimensions. Altogether, the reviewed studies revealed the scarcity of standardized nationally representative data for food prices and environmental indicators and suggest that diet sustainability might be increased without drastic dietary changes.

INTRODUCTION

According to the Food and Agriculture Organization, sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe, and healthy, while optimizing natural and human resources.[1] Efficiency, demand restraint, and system transformation have emerged as 3 main perspectives through which food system sustainability might be achieved.[2] Studies have thus focused on the mitigation of the environmental impact of food systems by changing patterns of production, consumption, and transformation.[2] Many authors have assessed the impact of food consumption on environmental indicators like greenhouse gas emissions (GHGEs), land use, or water footprint,[3–11] with GHGEs being studied the most. However, addressing

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the sustainable diet concept implies assessing the environmental concerns together with the healthiness and nutritional adequacy, the affordability, and the cultural acceptability of diets. Nutritional adequacy and healthiness both belong to the overall dimension of human health, which is, in fact, generally assessed either through nutritional quality indicators or health outcomes.

Because foods of plant origin exert a lower environmental impact than animal food products,[12,13] and because the health of vegetarians appears to be better than that of nonvegetarians,[14] the adoption of vegetarian or vegan diets is assumed to protect both health and the environment.[5,15–17] However, some nonvegetarian diets can also be healthy. Prudent diets with plenty of fruits, vegetables, nuts, legumes, and unrefined cereals and moderate amounts of red meat, fish, and dairy products have also demonstrated beneficial effects on health.[18] In addition, avoiding animal products does not necessarily provide health benefits.[14] Animal products are sole providers of some essentials nutrients, so that restrictive and monotonous plant-based diets may result in nutrient deficiencies with deleterious effects on health.[19,20] The harmful impact of animal-based products is only documented for red and processed meat at intakes higher than 50 g/d.[21] Moreover, the higher rate of mortality and chronic disease associated with Western diets is due not only to a high content of red and processed meat but also to excessive consumption of refined cereals, fried foods, soft drinks, sweets, and energy-dense, nutrient-poor food products.[18,21,22]

The sustainability of diets is not easy to assess because it requires high-quality indicators for each dimension as well as the possibility to link them. Many studies comparing the environmental impacts of different diets assessed only the energy or macronutrient (often only proteins) content of the diets.[9,15,16,23,24] In some cases, even the energy content was not indicated.[5,17,25–28] When using nutritional indicators that are too basic, the evaluation of the nutritional quality remains limited and could result in misleading conclusions about sustainability.

Some studies, however, did successfully take into account the health and nutrition dimension by modeling more environmentally friendly diets that fulfilled either food-based[5,9,23,29] or nutrient-based[30–34] recommendations or by relying on predictive public health models.[35,36] Some global and region-specific analyses have explored the health and environmental consequences of adopting dietary patterns such as vegetarian or Mediterranean diets.[37,38] Some of these studies have also assessed the affordability criteria, and most of them found that diets with good nutrition and low environmental impact could be achieved at no extra cost for the consumers.[16,30–32,39] The

modeling approaches used in these studies can be very instructive for achieving diet sustainability in the long term. Their main limitation is that they are based on arbitrary decisions about dietary changes. Food behaviors are influenced by a broad range of determinants,[40] and some simulated changes might not be considered reasonable or realistic to people, possibly neglecting cultural acceptability, which is an important dimension of diet sustainability.

Studies based on existing self-selected diets, ie, diets identified through food consumption surveys and thus actually consumed by individuals, may help to identify which food choices are currently the most sustainable, which should help in guiding more practical short-term action in a given population. A pioneering study from Coley et al.[41] used food consumption data to evaluate the environmental impact of existing diets at the individual level, estimated through calculation of the embodied energy of foods, ie, the anthropogenic part of the energy required for food production and likely to come from fossil-fuel sources. It revealed an extensive intervariability of this impact among typical UK diets, indicating the potential for significant reductions in fossil fuel–related GHGEs by simple changes in diet. However, neither the nutritional adequacy nor the healthiness of those diets was assessed.

To date, and to the best of the present authors' knowledge, only 10 studies used an epidemiological approach to assess the sustainability of self-selected existing diets by investigating both the environmental impact and the nutritional quality or healthiness of the diet at the individual level.[42–51] The aim of the present review was to examine those studies, which can be divided into two categories, depending on their aims and methodological approaches: (1) those that identified the primary dietary contributors to environmental impacts of diets and then simulated the effect of their reduction on diet sustainability characteristics, including environmental indicators and nutritional quality or healthiness (5 studies); and (2) those that analyzed the compatibility of diet sustainability dimensions, including environmental impact and nutritional quality or healthiness, on the basis of subclasses of self-selected diets (5 studies).

METHODS

The Web of Science database ("All databases" search) was searched for articles in English up to December 2015, using a combination of the following search terms: "greenhouse gas," "land use," "environmental impact," "environmental footprint," "climate impact," "climate change," "sustainable diet"; and "food consumption," "dietary intake," "dietary pattern," "self-selected diet," "individual diet"; and "nutri." Truncation symbols (asterisks) were applied where appropriate.

After removal of duplicates, this electronic search resulted in the identification of 107 articles that were then manually screened using the following inclusion criteria: study was based on individual food consumption data, and study assessed the environmental impact and nutritional quality or healthiness of the diet at the individual level. These inclusion criteria were chosen to select studies that used an epidemiological approach by performing statistical analysis of observed individual variability, thus warranting the robustness of the conclusions. Ten suitable studies met these criteria for inclusion.

Greenhouse gas emissions are expressed in kilogram of carbon dioxide equivalents (CO_2e), that is, kilogram of greenhouse gas weighted by global warming potential over a 100-year time frame, with carbon dioxide weighted as 1, methane weighted as 25, and nitrous oxide weighted as 298.

RESULTS

Simulating the impact of dietary changes on environmental and health dimensions of diets

The reduction of meat consumption has been identified as the main factor to reduce diet-related GHGEs and, therefore, to increase diet sustainability via food consumption changes.[52] The Food and Agriculture Organization attributed 14.5% of all human-induced GHGEs to the livestock sector.[53] The strategy of meat substitution has thus been investigated by various authors, but the hypothetical diet scenarios designed were not representative of actual food consumption.[5,9,15,16,54] The 5 studies that modeled substitution strategies starting from existing diets are summarized in Table 1[42–45,51] and reviewed below.

In their study based on dietary intake of 1724 adults participating in the British 2000–2001 National Diet and Nutrition Survey, Aston et al.[43] identified a dietary pattern low in red and processed meat that was already followed by a substantial fraction of the UK population. Using a modeling approach to quantify the risks of coronary heart disease, diabetes, and colorectal cancer, they estimated health and environmental benefits that would result if the proportions of vegetarians doubled and the remainder of the population adopted this dietary pattern that was low in red and processed meat. They noticed a high heterogeneity of red and processed meat intakes across the British population and confirmed red and processed meat consumption as the main factor in GHGE reduction, with emissions for men increasing by one-third from the lowest to the highest consumers of red and processed meat, and emissions for women increasing by one-quarter. Under the counterfactual scenario, diet-related GHGEs were reduced by 0.47 kg of CO_2e per person per day (12%). Estimates of the reduction in health risk were 9.7% and 6.4% for coronary heart disease (both nonsignificant), 12% (nonsignificant) and 7.5% (significant) for diabetes, and 12.2% and 7.7% for colorectal cancer (both significant) for men and women, respectively.

Temme et al.[44] assessed the environmental (land use) as well as the nutritional (intakes of saturated fatty acids and iron) characteristics of individual food consumption in 398 young Dutch women. Meat was identified as the most important contributor to diet-related land use in this population (contributing 39% to land use). The authors simulated the effects of replacing meat and dairy foods with plant-based products on land use and intakes of saturated fatty acids and iron. In their scenarios, meat and dairy products were replaced by the same amount of a plant-based dairy- or meat-replacing food that had a usage similar to that of the food being replaced. Thus, meat and cheese as sandwich filling were, for example, replaced by peanut butter or jam, and hot meal meats by tofu or eggs. Replacements were made with a probability proportional to the frequency of consumption in the baseline situation. This allowed selection of realistic choices by staying as close as possible to the existing eating habits. When all meat and dairy foods were replaced by plant-based products, land use was halved, estimated saturated fatty acids intake decreased by 4% of total energy, and total iron intake increased by 2.5 mg/d compared with the observed diet. However, about 10% of total iron in the observed diet was from heme iron, while almost all iron in the replacement scenarios was nonheme iron, known to have a lower bioavailability.[55] Moreover, meat and dairy food replacements were not isocaloric, and nutritional quality was only partially assessed. In particular, the authors pointed out the probable increase in sugar intake due to the high sugar content of some replacements foods (eg, sandwich toppings).

In their recent study based on dietary intake of 3818 individuals (7–69 years) participating in the Dutch National Food Consumption Survey 2007–2010, Temme et al.[51] evaluated the GHGEs of diets in girls, boys, women, and men separately and explored associations with diet composition, total food and energy intake, and macronutrient intakes. They observed that meat and cheese contributed about 40% and drinks (including milk and alcoholic beverages) 20% to daily GHGEs, similarly in all age and gender groups. By comparing groups per tertile of dietary GHGEs, they observed that the major differences between high- and low-GHGE diets were in meat, cheese, and dairy consumption as well as in soft drinks (girls, boys, and women) and alcoholic beverages (men) consumption.

| Reference	Study population	Food consumption data	Nutritional quality/health indicators	Environmental impact indicators/data	Methods	Main results	
						Main contributor to environmental impact	Effect of reduction of main contributor
Vieux et al. (2012)[42]	1918 adults (≥18 y), France	INCA 2 (2006–2007)	Energy density	GHGEs of 73 highly consumed foods, based on published values estimated by LCA	Estimated the GHGEs associated with self-selected diets. Evaluated the impact of (1) decreasing caloric intakes in order to meet individual energy needs and (2) meat reduction on diet-associated GHGEs	Meat and deli meat food group was the strongest contributor to dietary GHGEs (27%)	Meat reduction (50 g/d maximum) and removal of deli meat, without caloric compensations, reduced the mean GHGE levels by 12%. When energy loss was compensated by substitution with fruit and vegetables, mean GHGEs increased by 2.7%
						A strong positive relationship was found between total energy intake and dietary GHGEs	When total caloric intakes were reduced to meet individual energy needs, GHGEs decreased by either 10.7% or 2.4% for assumptions of low or moderate physical activity, respectively
Aston et al. (2012)[43]	1724 adults, UK	National Diet and Nutrition Survey (2000–2001)	Predicted reduction in risk of coronary heart disease, diabetes, and colorectal cancer, based on published meta-analyses	GHGEs of 45 food categories, based on published values determined by LCA	Estimated health and environmental benefits that would result if the proportions of vegetarians doubled and the remainder of the population adopted an existing low-RPM dietary pattern	RPM identified as a leading contributor to dietary GHGEs (men, 31%; women, 27%)	Under the counterfactual scenario, GHGEs were reduced by 12%. Risk reduction estimates were 9.7% and 6.4% for coronary heart disease, 12% and 7.5% for diabetes, and 12.2% and 7.7% for colorectal cancer for men and women, respectively
Temme et al. (2013)[44]	398 females (19–30 y), Netherlands	National Dutch Food Consumption Survey (2003)	Iron and SFA intakes	Land use, determined by using published values for primary agricultural products and a conversion model to ascertain land use of foods as consumed	Simulated the effects on land use, SFA intake, and iron intake of replacing meat and dairy foods with the same amount of plant-based products	Meat identified as the most important contributor to land use (39%)	When all meat and dairy foods were replaced by plant-based products, land use was halved, estimated SFA intake decreased by 4% of total energy, and total iron intake increased by 2.5 mg/d compared with the observed diet
Biesbroek et al. (2014)[45]	35 057 adults, Netherlands	EPIC-NL cohort	Mortality hazard ratio	GHGEs and land use of 254 food items; data provided by Blonk Consultants, estimation by LCA	Investigated the associations of dietary GHGEs and land use with mortality risk. Estimated the effect of substituting 35 g/d of meat with an equal amount of different food groups	Meat identified as the main contributor (≈30%) to dietary GHGEs and land use. GHGEs and land use of usual diet were not associated with all-cause or cause-specific mortality	Substituting 35 g of meat per day with an equal amount of vegetables, fruits, fish, or cereal/rice/couscous resulted in lower GHGEs and land use as well as decreased all-cause mortality risk

(continued)

Table 1 Continued

Reference	Study population	Food consumption data	Nutritional quality/health indicators	Environmental impact indicators/data	Methods	Main contributor to environmental impact	Effect of reduction of main contributor — Main results
Temme et al. (2015)[51]	3818 adults (7–69 y), Netherlands	Dutch National Food Consumption Survey (2007–2010)	Total fat, saturated fat, protein (animal and vegetable), carbohydrates (mono-/di- and polysaccharides), fiber, alcohol	GHGEs of 254 foods, estimated by standardized LCA and provided by Blonk Consultants. Data extended on the other reported foods	Estimated dietary GHGEs for girls, boys, women, and men. Evaluated differences in diet composition, total food and energy intake, and macronutrient intakes between 2 classes of diets (higher and lower GHGEs) for each gender/age group	Meat and cheese contributed about 40% and drinks (including milk and alcoholic drinks) 20% to daily GHGEs; these percentages were similar in all age and gender groups	A lower intake of energy, especially from animal-based foods (mainly meat and cheese) and/or by replacement with plant-based foods, is associated with a reduced environmental load as well as a lower SFA intake and a higher fiber intake in children and adults

Abbreviations: EPIC-NL, European Investigation into Nutrition and Cancer–Netherlands; GHGEs, greenhouse gas emissions; INCA 2, Second Individual and National Survey on Food Consumption; LCA, life cycle analysis; RPM, red and processed meat; SFA, saturated fatty acid.

Differences in the type of meat consumed had the greatest effect on differences in GHGEs. Moreover, compared with diets in the highest tertile of GHGEs, those in the lowest tertile contained significantly less energy, fat (especially saturated fats), animal protein, and alcohol (especially in men) and significantly more vegetable protein, carbohydrates, and fiber. Hence, those results suggest that reducing energy intakes, especially from animal-based foods and sugar- and alcohol-containing drinks, will help reduce the environmental impact of diets.

In another sample of Dutch adults (n = 40 011 adults participating in the EPIC [European Prospective Investigation into Cancer and Nutrition]–Netherlands cohort study), Biesbroek et al.[45] investigated the associations of GHGEs and land use of usual diets with mortality risk and also estimated the effect of meat substitution scenarios on health and the environment. In this population, total meat intake, which represented 3.6% of daily weight intake (and 11% of daily energy intake), was identified as the main contributor to environmental impact by accounting for approximately 30% of both dietary GHGEs and land use. The environmental impact (GHGEs and land use) of usual diets was not associated with all-cause or cause-specific mortality risk, indicating that an environmentally friendlier diet is not necessarily a healthier diet. However, the substitution scenarios showed that replacing 35 g of meat per day by an equal amount of vegetables, fruits, fish, or cereal/rice/couscous would lower both GHGEs and land use and would decrease the all-cause mortality risk. Moreover, those substitutions were not isocaloric or equivalent with regard to nutrient content, possibly resulting in modeled diets with poorer nutritional quality.

In their study based on food consumption data from 1918 adults participating in the latest French national dietary survey, the INCA 2 (Second Individual and National Survey on Food Consumption), Vieux et al.[42] estimated the GHGEs associated with self-selected diets and modeled the impact on diet-related GHGEs of decreasing caloric intakes in order to meet individual energy needs (scenarios 1 and 2) and of reducing meat consumption (scenarios 3 and 4). The meat and deli meat food group was the strongest contributor to diet-associated GHGEs: its mean contribution to emissions (27%) was more than twice as high as that generated by other food groups, whereas its mean contribution to diet quantity was one of the smallest (4%). The mean value for diet-related GHGEs was 4170 g (SD, 1162 g) of CO_2e per day, with men having on average higher GHGEs than women. Beyond these average numbers, a wide interindividual variability was observed for diet-related GHGEs. Figure 1 reveals a
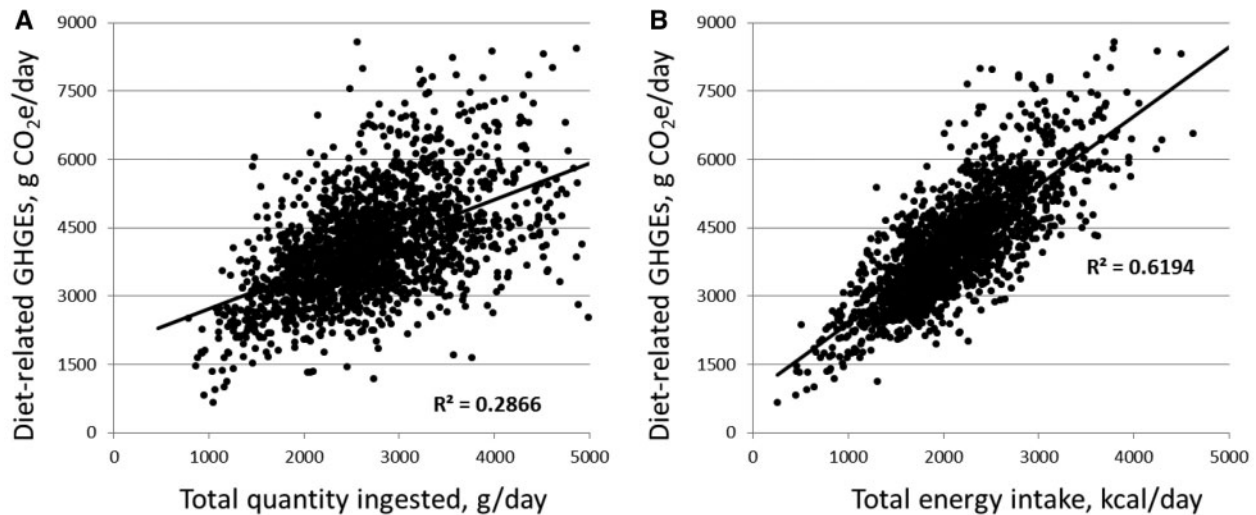
Figure 1 **Relationship between total quantities ingested and diet-related GHGEs (panel A) and between total energy intake and diet-related GHGEs (panel B) for adults participating in the INCA 2 study (n = 1918).** Adapted with permission from Vieux et al.[42] after recalculation of diet-related GHGEs for 391 GHGE food values (instead of 73). *Abbreviations*: CO_2e, carbon dioxide equivalents; GHGEs, greenhouse gas emissions; INCA 2, Second Individual and National Survey on Food Consumption.

positive correlation between total ingested quantities (including water and other beverages) and diet-related GHGEs (Figure 1, panel A). A stronger positive relationship was observed between total energy intake and diet-related GHGEs (Figure 1, panel B). In agreement with these relationships, diet-related GHGEs decreased in the scenarios in which energy intakes were reduced to meet individual energy needs. Compared with the current situation, mean reductions of 240 kcal/d and 10.7% of diet-related GHGEs were observed under the assumption of a low physical activity for all people (scenario 1), and mean reductions of 57 kcal/d and 2.4% of diet-related GHGEs were observed under the assumption of a moderate physical activity for all people (scenario 2). Both scenarios of meat reduction induced a decrease in dietary energy density, with or without isocaloric compensation. Moreover, meat reduction induced mean decreases of 35 kcal/d and 4.1% of diet-related GHGEs in scenario 3 (20% reduction in meat and/or deli meat intake) and mean reductions of 133 kcal/d and 12% of diet-related GHGEs in scenario 4 (meat reduction to reach 50 g/d maximum and removal of deli meat). Scenario 4 was thus the most efficient regarding potential reduction in GHGEs. However, when the energy loss (−133 kcal/d) associated with the meat reduction (−46 g/d) was compensated for, the subsequent decreases in diet-associated GHGEs were only 7.2% and 3.5% when the replacements were made with mixed dishes and dairy products, respectively. Moreover, when the substituted items were fruit and vegetables, the quantity needed to compensate for the energy loss was 426 g/d, actually leading to a 2.7%

increase in the mean diet-related GHGEs. One limitation of this study was the partial evaluation of nutritional diet quality, assessed by energy density only.

Two key messages arise from this first set of studies based on self-selected diets. First, while reduction of meat consumption was confirmed as one of the main factors to mitigate the diet-related environmental impact, those studies also revealed that the choice of meat replacement foods is crucial. The importance of ruminant meat as the main driver of diet-related GHGEs reinforces the rationale for increasing the consumption of plant-based foods to achieve more environmentally friendly and healthy diets. However, meat reduction per se does not necessarily lead to GHGE reduction and may even induce the opposite trend, depending on what food substitute is selected to compensate for the energy loss. A lack of accurate data limited the evaluation of the impact of the source (eg, locally produced vs air-shipped) and the production mode (eg, greenhouse vs open-air) of the plant food substitutes. The source and the production mode, however, might be key determinants of the eventual GHGEs and sustainability of the diet. Furthermore, a recurrent limitation of those studies was the weakness of the assessment of the nutritional quality. When considered, the nutritional quality of diet was only partly assessed, and energy intake was not always balanced when meat consumption was reduced. Lack of or only partial assessment of nutritional quality in meat-reduction scenarios may hide nutritional inadequacy, eventually leading to nonsustainable modeled diets. Thus, particular attention should be paid to the assessment of the nutritional quality of diet, and the

recommendation for meat reduction should be combined with recommendations on meat replacement foods, while considering nutritional adequacy, environmental impact, and acceptability dimensions at once.

The second main result from the first set of studies is that reducing energy intake is another main factor in reducing diet-related GHGEs. In particular, a strong positive correlation was found between total energy intake and diet-related GHGEs of French adults.[42] Moreover, considering most French adults have a low level of physical activity, just reducing food consumption to match the estimated energy requirements of each person may lead to a 10% decrease in GHGEs without the need to modify their habitual food patterns.[42] It seems obvious that simply reducing energy intake will reduce the environmental impact of diets, but this is rarely emphasized as such. In fact, some modeling studies that have analyzed the impact of environmental variables of adopting healthier food patterns did simulate a decrease in total energy intake without explicitly acknowledging it. For instance, two highly cited papers estimated the GHGE reduction associated with a simulation of meat consumption reduction without estimating the loss of energy associated with this reduction and without compensating for this loss.[26,27] More recently, a study concluded that adhering to the Mediterranean pyramid would reduce GHGEs by 72% compared with the mean Spanish diet as assessed by Food and Agriculture Organization food balance sheets.[28] Yet when the energy content of the recommended Mediterranean diet was estimated (on the basis of data provided by the authors in a supplementary table), this diet contained 61% less energy than the Spanish average diet and had thus, not surprisingly, a lower impact on GHGEs. In another recent study, two modeled diets derived from the average European diet to be vegetarian or to follow the German dietary recommendations were found to have a lower water footprint (−23% and −38%, respectively).[34] However, the modeled diets contained approximately 20% less energy than the average reference diet, suggesting that a large part of the positive influence of those diets on the environment could be related to their lower energy content. Therefore, encouraging frugality should be one of the first strategies for promoting sustainable diets in industrialized settings because it has the potential to help tackle both health and environmental concerns, with no prejudice on financial affordability. This is in line with public health recommendations that promote small daily reductions in energy intake to address the obesity epidemic and the related health conditions.[56] However, the cultural acceptability of eating less may prove challenging.[57]

Compatibility of diet sustainability dimensions

The 5 studies that assessed the compatibility of diet sustainability dimensions categorized individuals into subclasses according to the characteristics of their diet, such as nutritional quality or food group consumption. These studies are summarized in Table 2[46–50] and reviewed below. Diet-related GHGEs and nutritional adequacy or healthiness were then evaluated for each subclass. Two of those 5 studies also assessed diet cost.

In a study based on the French INCA 2 survey (n = 1918 adults), the main objective was to analyze the relation between GHGEs and the nutritional quality of diets.[46] Individuals were categorized into 4 classes on the basis of the nutritional quality of their diet. The GHGEs, food consumption, and nutrient intakes of each group were then evaluated. Nutritional quality was assessed through 3 indicators: the mean adequacy ratio, the mean excess ratio, and the dietary energy density. After adjustment for age, sex, and energy intake, a higher consumption of fruit and vegetables was associated with higher diet-related GHGEs, whereas a higher consumption of starches, sweets and salted snacks, and fats was associated with lower diet-related GHGEs. Accordingly, adjusted diet-related GHGEs were positively correlated with the mean adequacy ratio and negatively correlated with the mean excess ratio and the energy density. In addition, at a given level of energy intake, high-nutritional-quality diets were associated with significantly higher diet-related GHGEs than were low-nutritional-quality diets (+9% and +22% for men and women, respectively; $P < 0.0001$ for both sexes), showing a possible incompatibility between the nutrition and environmental dimensions in existing diets.

In the next study, which was based on the same study sample, the objective was to identify more sustainable diets among existing self-selected diets.[47] Individuals were categorized into 3 classes of diets: "lower carbon," "higher quality," and "more sustainable" diets, defined, respectively, as having daily GHGEs lower than the sex-specific median value, a nutritional quality score higher than the sex-specific median value, and a combination of both criteria. The score used to assess nutritional quality was the comprehensive PANDiet (probability of adequate nutrient intake) index, a measure of diet quality that indicates overall nutrient adequacy.[58] Diet cost, a proxy for affordability, and energy density, an indicator of poor nutritional quality, were also assessed. The dietary characteristics of the higher-quality, lower-carbon, and more sustainable diets were compared with the mean values for the whole population (referred as the "average" diets). The results confirmed that the 3 sustainability dimensions were not necessarily compatible with one

Table 2 Summary of methods and main results of the second set of reviewed studies, ie, those that analyzed the compatibility of diet sustainability dimensions on the basis of subclasses of self-selected diets

| Reference	Study population	Food consumption data	Nutritional quality/health indicators	Environmental impact indicators/data	Cost data	Methods	Comparison of subclasses of diets	Other
Vieux et al. (2013)[46]	1918 adults (≥18 y), France	INCA 2 (2006–2007)	MAR, MER, energy density	GHGEs of 391 foods, estimated by a standardized hybrid input-output/LCA method and provided by Greenext	–	After adjustment for energy intake, evaluation of the associations between dietary GHGEs and (1) 3 nutritional indicators (MAR, MER, energy density), (2) the consumption of food groups, and (3) 4 nutritional classes of self-selected diets	At a given level of energy intake, high-nutritional-quality diets were associated with significantly higher diet-related GHGEs than were the low-nutritional-quality diets, for both men and women	After age, sex, and energy-adjustment, a higher consumption of fruit and vegetables was associated with higher diet-related GHGEs, whereas a higher consumption of starches, sweets, salted snacks, and fats was associated with lower diet-related GHGEs
Masset et al. (2014)[47]	1918 adults (≥18 y), France	INCA 2 (2006–2007)	PANDiet score	GHGEs of 391 foods, estimated by a standardized hybrid input-output/LCA and provided by Greenext	Food prices from Kantar World panel database (2006)	Analysis of the GHGEs, nutritional quality, diet composition, and cost of 3 classes of self-selected diets ("lower carbon," "higher quality," and "more sustainable")	The "more sustainable" diets, consumed by ≈20% of adults, had significantly lower GHGEs (approx. −20%) and a lower daily cost (€/d) than the "average" diets, although the cost per kilocalorie was not different	Two main factors were identified as resulting in more sustainable diets: reduced energy intake and reduced energy density
Soret et al. (2014)[48]	73 308 Adventists, USA and Canada	Adventist Health Study 2 cohort	Mortality rate, hazard ratio	GHGEs of 210 foods, estimated by implementing LCA and on the basis of published GHGE values	–	Comparison of the GHGEs and mortality associated with 3 self-selected dietary patterns adjusted to 2000 kcal/d: vegetarians, semivegetarians, and nonvegetarians	When compared with findings in nonvegetarians, mean reduction in total GHGEs was 29.2% and 21.6% for the vegetarian and semivegetarian diets, respectively, and all-cause mortality risk was 9%–14% lower among vegetarians and semivegetarians	

(continued)

Table 2 **Continued**

Reference	Study population	Food consumption data	Nutritional quality/health indicators	Environmental impact indicators/data	Cost data	Methods	Main results — Comparison of subclasses of diets	Other
Scarborough et al. (2014)[49]	55 504 adults (>20 y), UK	EPIC-Oxford cohort	Total fat, saturated fat, protein, carbohydrate, total sugar, fiber	GHGEs of 289 foods, constructed from published data for 94 foods (Food Climate Research Network and WWF 2009)	–	After adjustment for age, sex, and energy intake, estimation of the difference in dietary GHGEs between self-selected high/medium/low meat-eaters, fish-eaters, vegetarians, and vegans in the UK	Adjusted mean GHGEs in kg of CO_2e/d were 7.19 for high meat-eaters ($\geq$100 g/d), 5.63 for medium meat-eaters (50–99 g/d), 4.67 for low meat-eaters (<50 g/d), 3.91 for fish-eaters, 2.89 for vegetarians, and 2.89 for vegans	Significant trends toward lower consumption of total fat, saturated fat, and protein and higher consumption of carbohydrate, total sugar, fiber, and fruit and vegetables as consumption of animal-based food decreased
Monsivais et al. (2015)[50]	24 293 adults ($\geq$39 y), UK	EPIC-Norfolk cohort	Accordance with DASH dietary pattern	GHGEs of 289 foods, constructed from published data for 94 foods (Food Climate Research Network and WWF 2009)	Food prices from MySupermarket.com (2012), adjusted for preparation and waste	After adjustment for age, sex, and dietary energy, evaluation of the association between accordance with the DASH dietary pattern and the GHGEs and retail costs of diets	Greater accordance with the DASH dietary pattern was associated with lower dietary GHGEs and higher dietary costs	Accordance with the "vegetable," "low-fat dairy," and "foods high in sugars" DASH groups was positively associated with GHGEs

Abbreviations: DASH, Dietary Approaches to Stop Hypertension; EPIC, European Investigation into Nutrition and Cancer; GHGE, greenhouse gas emissions; INCA 2, Second Individual and National Survey on Food Consumption; kg of CO_2e, kilogram of carbon dioxide equivalents; LCA, life cycle analysis; MAR, mean adequacy ratio; MER, mean excess ratio; PANDiet, probability of adequate nutrient intake; WWF, World Wildlife Fund.
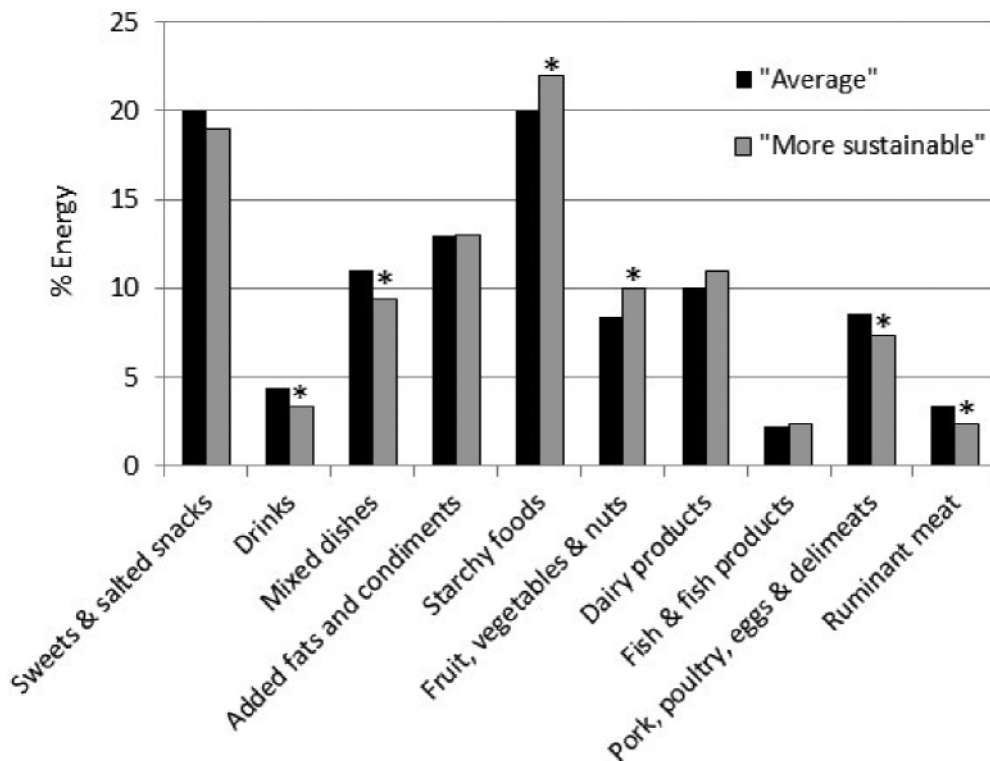
Figure 2 **Energy contribution of main food groups to the diets classified as average (whole sample, n = 1142 women) and more sustainable (n = 229) for women participating in the INCA 2 survey.** The average diets represent mean intakes in women; more sustainable diets were those with both diet-related GHGEs under the median and a PANDiet score above the median; Adapted with permission from Vieux et al.[47] Values are means. Asterisks indicate a significant (*P* < 0.01) difference between the average diet and the more sustainable diets, assessed with analysis of means. *Abbreviations*: GHGEs, greenhouse gas emissions; INCA 2, Second Individual and National Survey on Food Consumption.

another: lower-carbon diets were associated with lower cost but also with lower nutritional quality, and higher-quality diets were associated with both higher cost (per day and per kilocalorie) and higher GHGEs (per day and per kilocalorie). Nevertheless, more sustainable diets were identified by the authors. Those diets were consumed by approximately 20% of adults and had significantly reduced GHGEs (by 19%/d and 17%/d for men and women, respectively) and a lower daily cost (euros per day) than the average diets, although the cost per kilocalorie was not significantly different. Two main factors were identified as resulting in those more sustainable diets: reduced energy intake and reduced energy density. The energy contribution of starchy foods, fruit, vegetables, and nuts was higher than that in the average diets, whereas the energy contribution for meat, mixed dishes, and alcoholic drinks was lower (Figure 2 shows the results for women). Although statistically significant, the magnitudes of the above-listed differences were quite small, and there was no difference in the energy share of dairy products and sweets and salted snacks. Hence, dietary choices that allowed more sustainable diets to be reached were not

dramatically different from the food choices observed in the average diets.

In their study based on self-selected diets of adults participating in the EPIC-Oxford cohort, Scarborough et al.[49] categorized individuals into 6 dietary classes defined by levels of meat consumption (high meat-eaters [≥100 g/d], medium meat-eaters [50–99 g/d], low meat-eaters [<50 g/d], fish-eaters, vegetarians, and vegans) and compared the dietary GHGEs of each class after standardization to a diet of 2000 kcal/d. The assessment of nutritional quality was based on daily intakes of energy, nutrients (total fat, saturated fat, protein, carbohydrates, total sugars, dietary fibers), and fruit and vegetables. This study showed highly statistically significant differences ($P < 0.0001$) in dietary GHGEs between the 6 classes after adjustment for age and sex, with progressively higher emissions for classes with greater intakes of animal-based products. The age-, sex-, and energy-adjusted mean GHGEs (in kg of CO_2e/2000 kcal) were 7.19 for high meat-eaters (≥100 g/d), 5.63 for medium meat-eaters (50–99 g/d), 4.67 for low meat-eaters (<50 g/d), 3.91 for fish-eaters, 3.81 for vegetarians, and 2.89 for vegans (Figure 3). The authors also
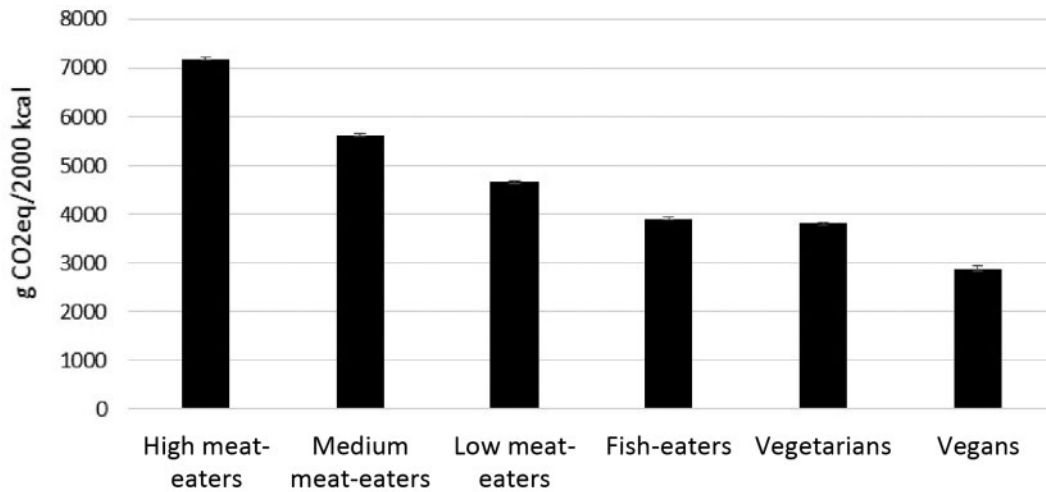
Figure 3 **Mean dietary GHGEs per 2000 kcal for high meat-eaters (≥100 g/d; n=8286), medium meat-eaters (50–99 g/d; n=11971), low meat-eaters (>0 and<50 g/d; n=9332), fish-eaters (n=8123), vegetarians (n=15 751), and vegans (n=2041) in the United Kingdom.** Adapted with permission from Scarborough et al.[49] *Abbreviations*: CO$_2$e, carbon dioxide equivalents; GHGEs, greenhouse gas emissions.

observed significant trends toward lower consumption of total fat, saturated fat, and protein and higher consumption of carbohydrate, total sugar, fiber, and fruit and vegetables as the quantity of animal-based products in the diet decreased. Assuming that the average daily energy intake is 2000 kcal, they estimated that moderate dietary changes like moving from the predefined high meat-eater diet to the low meat-eater diet would reduce an individual's carbon footprint by 2.52 kg of CO$_2$e per day.

Using dietary data from the Adventist Health Study 2, a large prospective cohort study in the United States and Canada, Soret et al.[48] also categorized individuals according to their dietary patterns. They defined 3 dietary classes according to the reported combined intake of all meats, including fish: vegetarians who rarely or never consumed meats (<1 time/mo), semivegetarians who consumed meats more than1 time per month but less than 1 time per week, and nonvegetarians who consumed meats at least 1 time per week. The main objective was to compare the GHGEs associated with the 3 dietary patterns. In parallel, the mortality rates of the 3 dietary classes of individuals were compared. Except for meat and plant foods, the proportional contribution to GHGEs from other food categories (dairy, eggs, beverages, other foods) was comparable across the 3 diets. With the nonvegetarian diet as reference, the mean reductions in total GHGEs were 29.2% and 21.6% for the vegetarian and semivegetarian diets, respectively. Hence, knowing that moving from the nonvegetarian to the semivegetarian diet equates to a difference of 25 g of ground beef per day (approx. one-third of a standard serving), the authors noted that relatively minor

changes in meat consumption could lead to nontrivial reductions in diet-related GHGEs. Moreover, with the average American meat intake being twice as high as that of nonvegetarians in the Adventist Health Study 2, GHGE reduction could be greater if compared with the typically nonvegetarian American diet. From a health point of view, the mortality rate was 16% to 17% higher among nonvegetarians compared with vegetarians and semivegetarians. After adjustment for a wide range of lifestyle factors that included smoking, alcohol use, exercise, and sleep and for some sociodemographic variables, all-cause mortality risk was 9% to 14% lower among vegetarians and semivegetarians compared with nonvegetarians. Hence, this study suggests that, in addition to benefiting the climate, reduced consumption of meat also benefits health. However, the authors wisely mentioned that individuals might not opt for plant foods that provide optimum nutrition to compensate for meat reduction, and although results showed that moderate differences in meat intake were associated with nontrivial reductions in GHGEs and improved health outcomes, this does not imply that diets lower in GHGEs are systematically healthy.

Recently, using data from the EPIC-Norfolk UK cohort, Monsivais et al.[50] analyzed the dietary intakes of more than 24 000 adults for their accordance with the 8 targets of the Dietary Approaches to Stop Hypertension (DASH) dietary pattern. The authors evaluated the association between accordance with the DASH dietary pattern and the GHGEs and estimated costs of diets. Accordance with the DASH dietary pattern was assessed through a score based on the consumption of 8 food groups and nutrients, adjusted for
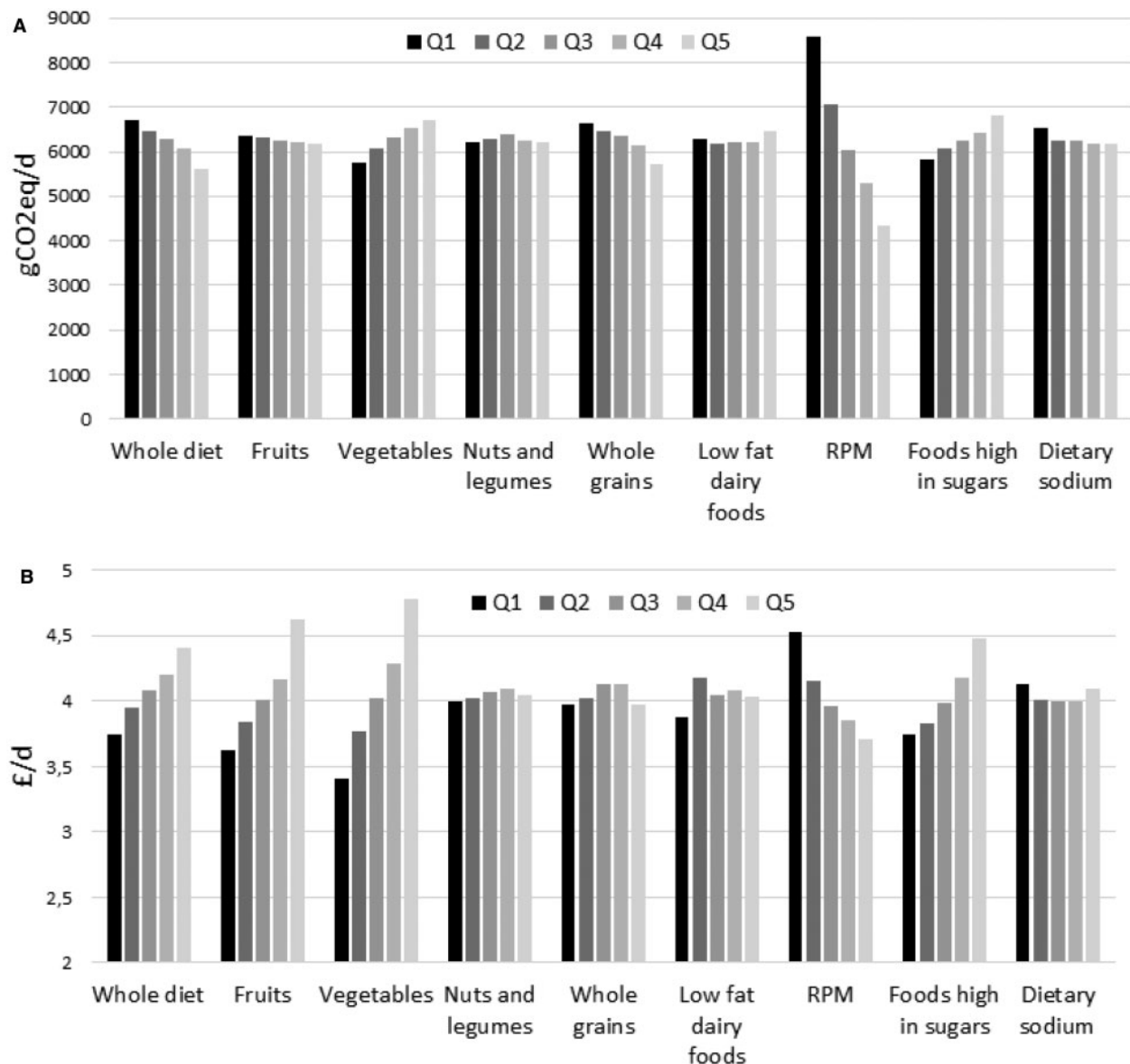
Figure 4 **Mean dietary GHGEs (panel A) and mean dietary cost (panel B) by quintile of accordance with the DASH diet as a whole and with food groups of the DASH diet.** Adapted with permission from Monsivais et al.[50] *Abbreviations*: CO_2e, carbon dioxide equivalents; DASH, Dietary Approaches to Stop Hypertension; GHGEs, greenhouse gas emission; Q1, lowest accordance with DASH diet; Q5, highest accordance with DASH diet; RPM, red and processed meat.

energy (positive scoring for 5 groups: fruits, vegetables, nuts and legumes, whole grains, and low-fat dairy foods; and negative scoring for 3 groups: red and processed meats, foods high in added sugars, and sodium). The results showed that greater accordance with the DASH dietary targets was associated with lower dietary GHGEs and higher dietary costs (Figure 4). Adults in the highest quintile of the DASH accordance scores consumed diets with GHGEs 16% lower (−1.1 kg of CO_2e/d) but 18% more costly (+£0.67/d) than adults in the lowest quintile. The authors also examined the associations with each of the 8 DASH dietary targets. Consumption of more fruits, more whole grains, less

red and processed meat, or less sodium was associated with lower GHGEs, whereas consumption of more vegetables, more low-fat dairy foods, or less high-sugar foods was associated with higher GHGEs (Figure 4, panel A). Hence, depending on the food group in which the change occurs, health and environmental goals can either match or be incompatible. In terms of affordability, while highest accordance with the red and processed meat DASH target (ie, lower consumption) was cost saving, diets higher in fruits and vegetables and lower in high-sugar foods were associated with a higher cost (Figure 4, panel B). Moreover, the remaining food groups (nuts and legumes, whole

grains, low-fat dairy foods, and sodium) showed no association or only a small difference in diet cost between the most- and the least-accordant diets. Hence, though results confirmed that the most DASH-accordant diets were 18% more costly than unhealthy diets, food group analysis revealed that changes in some food categories can be cost neutral, indicating a potential to make the cost and health dimensions compatible.

There are two key messages arising from this second set of studies. First, the different sustainability dimensions are not necessarily compatible with each other. In particular, in contradiction with the widely accepted view that healthy diets are also good for the environment, when nutritional quality was assessed, it was not necessarily convergent with the environmental dimension.[46,47] This was attributed to the known inverse relationship between nutritional quality and dietary energy density.[59,60] Thus, even if self-selected diets with better nutritional quality were characterized by a predominance of foods with low GHGEs per 100 g, such as starches, fruits, and vegetables, ultimately these diets had a greater impact than low-quality diets because they contained larger total food quantities. Hence, while increasing nutritional quality implied decreasing energy density, which is favorable for preventing obesity and promoting overall health,[18] it also implied increasing daily diet-related GHGEs, which was detrimental from an environmental perspective. Moreover, consumption of food groups with both low GHGEs and greater affordability, such as high-sugar foods and starchy foods, resulted in reduced nutritional quality and, possibly, detrimental health effects. The risk of inducing extra deaths while reducing GHGEs was previously demonstrated in a scenario in which low-GHGE foods, including sweets and soft drinks, were subsidized.[36] The reviewed studies also pointed out contradictions between the economic and the nutritional dimensions of diet sustainability, similarly to previous studies showing that healthy diets are more expensive than unhealthy ones.[61] It is therefore paramount to promote all sustainability dimensions at the same time because supporting only one of them may result in a deterioration of the others.

The second main finding emerging from the second set of reviewed studies is that some existing diets consumed by a substantial fraction of the population are more sustainable than others, while including meat. This indicates that increasing diet sustainability, which includes respecting the acceptability exigency, does not require drastic or unrealistic food changes. Previous studies that aimed at identifying diets both healthy and environmentally friendly were based on special diets such as those adopted by vegetarian or vegan subjects or diets modeled to fulfill a set of recommendations.[5,9,15–17,23–25,39] However, the realism of such scenarios is questionable, since the prevalence of vegetarianism is quite low in industrialized countries (eg, estimated to ≈2% in the French[62] and US[63] populations). In addition, some studies suggest that a large proportion of the population is not yet ready to consume a fully plant-based diet.[64,65] In contrast, Masset et al.[47] found that approximately 20% of French adults had diets that could be considered more sustainable because they combined higher nutritional quality and lower GHGEs with no increase in diet cost. The reduction in GHGEs observed with these more sustainable diets was close to the 20% reduction target set for 2020 by European Union member states.[66] Moreover, though still questionable in terms of acceptability, the dietary changes suggested to achieve the GHGE reduction were more moderate in terms of food choices than proposed scenarios that avoided meat or animal-based products.[5,9,15,16] Scarborough et al.[49] also showed that moving from a high level ($\geq$100 g/d) to a low level ($<$50 g/d) of meat consumption can lead to nontrivial reductions in GHGEs. Finally, Monsivais et al.[50] identified small changes in consumption of some food groups that were compatible with the health, environmental, and cost dimensions of diet. Therefore, there is no need to avoid entire food categories to achieve diet sustainability, and the long-standing advice of favoring food variety is still valid in this context.

Overall, the 10 reviewed studies revealed a lack of relevant and good-quality datasets for assessing the cost and environmental impact of diets. Only 2 studies[47,50] considered the affordability dimension of sustainability by analyzing diet cost, with only 1 of them[47] based on average and nationally representative data for food prices. To assess the environmental impact of diet, most of the reviewed studies used a compilation of published environmental data that came from heterogeneous studies conducted under different life cycle analysis modeling hypotheses or specific geographical situations or production modes, hence compromising the representativeness and relevance of the dataset. In contrast, 4 of the reviewed studies[45–47,51] used GHGE data built from standardized methods incorporating information specific for the corresponding national situation and applied to all food items in the dataset, thus warranting reliably sourced data representative of national food consumption and production modes. However, such datasets do not allow evaluation of the impact of choosing a specific food production mode (eg, open-air vs greenhouse) or source (eg, locally produced vs air-shipped) on the sustainability of the diet. Hence, future research on diet sustainability would benefit from the development and increased availability of standardized, nationally representative databases for food prices and

environmental indicators or from databases that include different GHGE estimates by food item, depending on the source and mode of production of the food. Such databases would allow improved assessment of the affordability and environmental impact of diets. Moreover, it appears that none of the identified studies assessed any dimensions of environmental footprint other than GHGEs and land use. This highlights the potential lack of analysis of other environmental impacts such as the water or nitrogen footprint of self-selected diets. Nevertheless, food GHGEs were found to strongly correlate with water eutrophication and air acidification,[13] and decreases in diet-related GHGEs tended to correspond with decreases in water use, nitrogen release, and land use,[67] suggesting the relevance of GHGEs as a marker of the environmental impact of diets. Other sustainability dimensions such as biodiversity should still be considered.

Overall, this review suggests that, given the potential incompatibility of sustainable diet dimensions, future research on mitigation of the environmental impact of diet should adopt a holistic approach that integrates the assessment of nutritional adequacy, health impact, acceptability, affordability, and different environmental footprints. In particular, more research on the types of dietary changes that consumers are willing to consider and on methodologies or indicators that allow better assessment of the dimension of acceptability would help to identify more realistic alternative diets. Moreover, by highlighting the decisive effect of the foods chosen as substitutes for the more impactful ones, this review suggests using a whole-diet approach when identifying strategies to move toward more sustainable diets.

CONCLUSION

In recent years, the growing concern for environmental issues and food insecurity has emphasized the need to promote sustainable diets. The studies reviewed here used an epidemiological approach to assessing diet sustainability by investigating both the environmental impact and the nutritional quality or healthiness of diets at the individual level. By analyzing real self-selected diets, the studies allowed observation of the variety of real food choices rather than theoretical dietary patterns and, thus, better consideration of the critical dimension of cultural acceptability. Two groups of studies were reviewed: 5 studies evaluated the benefits that would result from a reduction in the main contributors to environmental impacts of diets, and 5 studies compared the environmental impact and nutritional quality or healthiness of subclasses of self-selected diets. Some key messages emerged from those studies. First, reductions in meat consumption and energy intake were identified

as main factors for reducing diet-related GHGEs. However, the choice of meat replacement foods is crucial, with some foods possibly leading to an increase in GHGEs when energy loss is balanced. Second, this review highlighted that only a few studies properly assessed the nutritional adequacy of diets by considering a large set of nutrients. In contrast, the majority of studies did not assess, or only partially assessed, nutritional quality, thus compromising the accuracy of sustainability assessment. Third, the reviewed studies highlighted that some dimensions of sustainability are not necessarily compatible with one another. In line with previous conclusions,[68] they confirmed that high nutritional quality is often associated with higher cost. In addition, they showed that high nutritional quality may be associated with greater environmental impact. Fourth, these studies suggested that diet sustainability might be increased without requiring drastic food choices like excluding entire food categories. Some existing diets consumed by a substantial fraction of the population were identified as being nutritionally adequate or healthy while respecting food diversity, tolerating some meat in the diet, and having lower environmental impact, thus allowing compatibility between the nutritional, environmental, affordability, and acceptability dimensions of diet sustainability. Finally, the whole set of reviewed studies revealed the scarcity of standardized and nationally representative data for food price and environmental indicators.

Future studies investigating the environmental impact of diets should consider all dimensions of diet sustainability. Particular attention should be paid to nutritional quality, which needs to be assessed through relevant nutrient-based indicators, and to cultural acceptability, a key – although often ignored – dimension of sustainability. Moreover, beyond the assessment of the environmental impact of diet and the identification of more sustainable diets, the question of which actions and tools would favor the adoption of such diets by consumers still needs to be addressed.

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