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Low Greenhouse Gas Emission Self-Selective Diets and Risk of Metabolic Syndrome in Adults 40 and Older: A Prospective Cohort Study in South Korea

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Background: The food system accounts for ∼40% of human-generated greenhouse gas (GHG) emissions. Meanwhile, daily diet selection also impacts human nutrition status and health.

Objectives: This study aimed to use the alternate Mediterranean Diet (aMED) score to evaluate the quality of a low-GHG emission diet and the association with risk of developing metabolic syndrome (MetS).

Methods: A total of 41,659 healthy participants without MetS 40 y of age or older were selected from the Health Examinees Study, an ongoing cohort study in South Korea from 2004. A dietary GHG emissions database was compiled following a national project and literature review. MetS was defined according to the Adult Treatment Panel III criteria of the National Cholesterol Education Program. The participants were grouped into quintiles based on 2,000 kcal–standardized daily diet-GHG emissions (Q1: the lowest energy-adjusted diet-GHG emissions). A multivariable logistic regression model was used to analyze the risk for MetS at follow-up. The aMED score was used to assess the diet quality of the different diet-related GHG emission groups.

Results: Females with lower energy-adjusted diet-related GHG emissions had significantly lower risks of developing MetS ($p = 0.0043$) than those with the highest energy-adjusted diet-related GHG emissions. In addition, the Q1 group, in comparison with the other groups, had a higher aMED score (3.02 for males and 3.00 for females), which indicated that the participants in this group had a diet that more closely matched the Mediterranean diet.

Discussion: These findings provide a reference for dietary guidance and other policies aimed toward improving dietary intake and reducing diet-related GHG emissions in South Korea and worldwide. https://doi.org/10.1289/EHP12727

Introduction

The food system is one of the most important factors leading to climate change.[1] Greenhouse gases (GHG) from the food system are generated primarily through three pathways: crop and livestock production, land-use change, and food-related activities beyond the farm gate.[2] GHG produced by the food system accounted for approximately one-third of the total GHG emissions in 2015.[1] Among the GHG emissions, which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O),[3,4] the production of CO_2 from land use is the largest,[5] and CH_4 and N_2O emissions dominate the dietary GHG emissions[6] are a main cause of global warming. The Copenhagen Accord in 2009 proposed that limiting the rise in global surface temperatures could reduce the risk of adverse effects associated with climate change.[7]

Climate change interacts with the food environment and nutrition status and can impact the occurrence of chronic noncommunicable diseases, such as cardiovascular and kidney diseases.[8,9] Notably, it has recently been demonstrated that dietary change by consumers, primarily regarding food-related activities beyond the farm gate, could deliver substantive environmental impacts on a scale comparable to that of the food producers.[2,10]

Accordingly, the concept of climate-friendly diets that benefit both human health and the environment is attracting considerable research attention.[11–13] The production of meat products has been found to have a disproportionately negative effect on GHG emissions,[14] and plant-based foods have been proposed as an alternative main food source.[15] In addition, vegetarianism is promoted by numerous researchers and organizations (such as the Vegetarian Society in the United Kingdom).[16,17] However, other studies have reported that reducing meat consumption threatens nutrition absorption and can cause deficiencies in key nutrients, such as iron and zinc.[18,19] A balanced diet that is neither only vegetarian nor only meat-dominant (such as the EAT-*Lancet* diet proposed at the *Lancet* Commissions, which aimed to use the best available evidence to propose a universal reference diet for the health of humans and the planet[20]) is particularly important and prominent for public health and the environment worldwide.[21] A global analysis has investigated the effects of healthy diet patterns on improving health and preventing the incidence of chronic diseases and found that optimum diets not only minimize the environmental impact but also have a positive influence on human health.[22]

Metabolic syndrome (MetS) and its components (abdominal obesity, elevated triglycerides, decreased blood high-density lipoprotein cholesterol, elevated fasting blood glucose, and elevated blood pressure) constitute some of the main risk factors for developing cardiovascular disease, diabetes, and stroke. The prevalence of MetS has increased rapidly in Korea, has affected over 30% of the population in 2007,[23] and subsequently remains at a high level.[24] Although the management of MetS includes performing sufficient exercise and attaining sufficient hours of sleep, it is also necessary to maintain a diet that is nutritionally balanced and includes plants and animal products.[25]

This study was conducted to determine whether an association exists between eating a healthier and climate-friendly diet and reducing the incidence of MetS in the South Korean population. Specifically, this study aimed to *a*) construct a food carbon footprint database based on the representative food consumed by the general population of South Korea, *b*) examine the association between diet-related GHG emissions and the incidence of MetS and its five components, and *c*) identify the diet combination that was associated with low diet-related GHG emissions rather than one certain food group using the alternate Mediterranean Diet (aMED) Score. The results of this study will serve as a useful foundation to inform policies aimed at improving diets to alleviate the urgent concern of the increasing MetS incidence while minimizing the environmental impact in South Korea and worldwide.

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Materials and Methods

Study Population

The Health Examinees (HEXA) study was a large-scale genomic cohort study conducted among the general population of South Korea that investigated epidemiological characteristics, genomic features, and gene–environment interactions associated with major chronic diseases.[26] The HEXA study was approved by the Ethics Committee of the Korean Health and Genomic Study of the Korean National Institute of Health and the institutional review boards of all participating hospitals (IRB No. E-1503-103-657). All participants provided informed written consent prior to participating in the study.

The ongoing HEXA study was initiated in 2004 and included the general population 40 y of age and older at 38 sites across South Korea. Participants who were seen at the baseline (2004–2013) and the first follow-up (2012–2016) HEXA studies were included in this study ($n = 65{,}642$; female $= 43{,}343$, male $= 22{,}299$). Participants with the following missing data were excluded from this study: biomarker values, food frequency questionnaire (FFQ) data, age information, and body mass index (BMI) values. Implausible total energy intake values (<800 and more than 4,000 kcal per day for males and <500 and more than 3,500 kcal per day for females)[27] were also excluded. To better assess the risk for the development of MetS, this study only included participants without MetS at baseline. In particular, participants with associated diseases, including hyperlipidemia, diabetes, stroke, transient ischemic attacks, angina pectoris, and myocardial infarction, were all excluded. A detailed flowchart showing the selection process is provided in Figure S1. In total, 41,659 participants (12,846 males and 28,813 females) were selected for inclusion in the current study.

Dietary Data

All participants completed an externally validated 106-item FFQ at the baseline and follow-up surveys.[28] The reproducibility and validity of the FFQ have been assessed using diet recollection over four seasonal 3-d, 24-h periods.[28] The questionnaire addressed the types of food consumed in the year preceding the baseline survey and the associated ingestion frequencies, portion sizes, and preparation methods involved.[26] Considering the interaction with outcome, we used the baseline FFQ information as the participants' daily dietary intake. With respect to GHG emissions related to daily food intake, this study focused on the amount of GHG emissions per unit of energy provided by the food rather than the GHG emissions per unit of the food weight. GHG emissions related to the individual diets were calculated according to a kilogram of CO_2 equivalents (kg CO_2 eq) per 1,000 kcal. The total energy intake was calculated using the Korean Standard Food Composition Table (ninth revision).[29] The HEXA FFQ data obtained were also linked with the Dietary Reference Intakes for Koreans (KDRIs; 2015) to minimize any calculation biases when calculating portion sizes (mainly with respect to vegetables, meat, dairy products, and fruit) of the 106 food types.

Furthermore, because the Mediterranean diet is believed to play a role in lowering the risk for several chronic diseases, a modified alternative Mediterranean Diet Score (aMED), developed using a semi-FFQ to quantify the diet, was adopted in this analysis to evaluate the diet quality and health benefit of a climate-friendly diet (low dietary GHG emissions). Trichopoulou et al.[30] developed the Mediterranean diet score, and Fung et al.[31] modified it to the aMED. Based on the aMED, the 106 food items of the HEXA FFQ data were classified into seven food groups (whole grain, vegetables, fruits, legumes, red and processed meat, fish, and alcohol), and information on the ratio of monounsaturated to saturated fat was added by linking the HEXA FFQ data and the Korean Standard Food Composition Table (ninth revision). The participants were assigned one point if they consumed greater than the median intake of each food group, excluding the "red and processed meats" and "alcohol" groups. Conversely, if they consumed less than the median values, they received zero points. The participants were assigned 1 point if they consumed less than the median intake of "red and processed meats." The participants received 1 point if they consumed between 5 and 15 g/d of ethanol. The total aMED score ranged from 0 to 8.

Considering the difference in food culture between the Mediterranean diet, which is abundant in MUFA from nuts and olive oils, and the Korean diet, which is abundant in carbohydrate and micronutrients from grains and vegetables, an additional association analysis between dietary GHG emissions and the Korean Food Balance Wheel (KFBW) was performed as proposed in the Korean Dietary Guidelines.[32] The KFBW mainly classifies the daily diet components into five groups (cereals, dairy products, fruits, vegetables, and meat/eggs/legumes). In the current study, first, the intake units of the 106 food items from the HEXA FFQ data were converted from grams per day to servings per day, and the 106 food items were assigned into the five KFBW groups. Then we could assess the consumption and GHG emission of the five KFBW groups from self-selected diet according to GHG emissions quintiles (GHG emissions of 106 food items are described in Tables S1 in detail, and GHG emissions of five KFBW groups consumed by participants from each quintile group are shown in Table S2).

Environmental Impacts and Links to Dietary Data

The GHG emissions were assessed using a life cycle assessment (LCA) method,[11] which is a comprehensive method that systematically and quantitatively describes various resources, energy consumption, and environmental emissions during the product's life cycle and evaluates their environmental impact.[33] Dietary GHG emissions accounted for all the GHG emissions from input to output that are involved in the food production chain.[13] However, at present, there are no comprehensive LCA databases available for Korean foods. Hence, an extensive review of the LCA literature was conducted at the beginning of this study to develop a food-related environmental impact database that focused on the diet-related GHG emissions for Korean foods. The viability of the LCAs was assessed as per the International Organization for Standardization (ISO 14040:2006/AMD 1:2020).

The GHG emission values were recorded in kilograms of CO_2 eq per kilogram of food[3] and were converted to kilograms of CO_2 eq per kilocalorie of food by linking the Korean Standard Food Composition Table (ninth revision). Carbon footprint data associated with the main food types were obtained from project reports of the Korea Ministry of Environment,[34–36] and the food items for which no carbon footprint data were available in Korea were preferentially searched and matched using data from neighboring countries, such as Japan.[37] Although Western countries have conducted more research in this area, data matching different production means with living habits has not been prioritized. For food items relating to the same product, such as apples and apple juice, the weighted values from the HEXA items were adopted. With respect to the food items for which no associated LCA study was found, data relating to a similar food item or an alternative food item were used; for example, data associated with carrots were used for deodeok (*Codonopsis lanceolata*). In addition, food items were excluded from the study if consumed infrequently (average intake <1 g/d). The average dietary GHG emissions per person per day were then calculated in kilograms of CO_2 eq after being standardized by 2,000 kcal according to the HEXA FFQ data.

Definition of MetS

According to the Adult Treatment Panel (ATP) III criteria of the National Cholesterol Education Program, MetS is diagnosed when three or more of the following five traits are identified: *a*) a waist circumference (WC) of $\geq$90 cm in males and $\geq$80 cm in females; *b*) serum triglycerides (TG) $\geq$150 mg/dL; *c*) serum high-density lipoprotein cholesterol (HDL-C) <40 mg/dL in males and <50 mg/dL in females; *d*) systolic blood pressure (SBP) $\geq$130 mmHg or diastolic blood pressure (DBP) $\geq$85 mmHg; and *e*) fasting plasma glucose $\geq$100 mg/dL.[24] All participants in the present study underwent anthropometric measurements (WC), clinical measurements (blood pressure), and fasting blood tests (lipid profiles and fasting blood glucose) at the baseline and follow-up HEXA surveys.[38] According to the results of the baseline measurements, participants were excluded from the current study if they met three or more of the ATP III criteria, and the participants who met three or more of the ATP III criteria according to the results of the follow-up biochemical analysis were grouped into the MetS group.

Additional Covariates

In the current analysis, all covariates, including anthropometric measurements, demographics, smoking and drinking statuses, lifestyles, and physical activity, were collected at the HEXA baseline survey. These covariates have been previously reported as potential confounders in epidemiological studies.[39] To diminish the potential for bias, we adjusted for these covariates in analytical models. The anthropometric measurements and questionnaires were collected and administered by well-trained and skilled staffs using consistent and standardized methods.[38] Height was measured to the nearest 0.1 cm and weight to the nearest 0.1 kg. BMI was calculated by dividing an individual's weight (kg) by the square of their height in meters (m^2). The BMI groups were then categorized as follows: low weight <18.5 kg/m^2, normal weight 18.5–25.0 kg/m^2, overweight 25.0–30.0 kg/m^2, and obese $\geq$30.0 kg/m^2. Self-reported age was used to classify the age group as "40–49 years," "50–59 years," "60–69 years," and "70–79 years." Participants were queried whether they drink alcohol and, if so, were defined as a "current drinker" and were then asked questions on the types (objective question with eight options: soju, beer, wine, makgeolli, sake, hard liquor, fruit wine, and others), frequencies (objective question with eight options: none or rarely, once per month, two or three times per month, once per week, two or three times per week, four to six times per week, once per day, and at least two times per day), and amounts (subjective question, amount in cups) of alcohol consumption. The ethanol contents were defined as 21%, 4.5%, 6%, 15%, 13%, 40%, 14%, and 18% for soju, beer, wine, makgeolli, sake, hard liquor, fruit wine, and others, respectively. The frequencies, amounts, and ethanol contents of each alcohol type were multiplied to calculate the total daily ethanol intake. Participants also answered the objective question, "Have you smoked more than 20 packs (400 cigarettes) in total so far?" and three options were listed: "No, never smoked," "Yes, but not now," or "Yes, still now." Corresponding to the answers, they were grouped into three smoking status groups: "never," "past smokers," or "current smokers," respectively. Physical activity was assessed based on questions regarding the duration (minutes or hours) and frequency (times per week or day) of exercise with sweat. "Physically active" was defined as performing more than 30 min of exercise with sweat more than twice a week.[40] Information about education was collected with the question "How long did you go to school?" with nine options: "never," "dropped out of elementary school," "graduated from elementary school or dropped out of middle school," "graduated from middle school or dropped out of high school," "graduated from high school," "graduated from college," "dropped out of university," "graduated from university," and "graduated from graduate school." Educational levels attained were then categorized: "below middle school," "high school," or "college or above." The missing values for the categorical covariates were grouped separately, and the missing values for continuous covariates were replaced with the median values.

Statistical Analyses

Considering the differences in dietary habits and sex hormone, all the analyses conducted in the current study were stratified according to sex. Participants were grouped according to the quintiles of the 2,000 kcal–standardized diet-related GHG emissions. The continuous variables (age, BMI, and total energy intake) were expressed as the mean $\pm$ standard error (SE), and the categorical variables (educational level, drinking status, smoking status, and physical activity) were presented as frequencies with percentages. The differences were tested by a chi-square test among the categorical variables and a generalized linear model for the continuous variables. A post hoc test for the continuous variables was performed using a Duncan test. The main analysis relating to the health effect of the energy-adjusted diet-related GHG emissions was conducted using a multivariable logistic regression model. The odds ratios (ORs) and 95% confidence intervals (CIs) for MetS in accordance with the quintiles of the energy-adjusted diet-related GHG emissions were estimated after adjusting for potential confounders, which included the three continuous and four categorical variables. All statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc.). A *p*-value of 0.05 was used to determine statistical significance, with the highest GHG emissions quintile (Q5) as the reference group.

Results

Figure 1 shows the GHG emissions of several commonly consumed representative Korean food items obtained from the HEXA FFQ data; the GHG emissions of all 106 food items are listed in Table S1. With respect to the per unit of weight, the GHG emissions of meat (such as beef and pork) are greater than those of vegetables and fruit; however, in relation to the per unit of energy released, the amounts of GHGs emitted from meat are not always higher than those from vegetables and fruits. For example, with respect to the per unit weight, the GHG emissions of pork and onion are 4.25 and 0.38 kg of CO_2 eq/kg, respectively, whereas for the per unit of energy released, the GHG emissions are 1.00 and 1.40 kg CO_2 of eq/1,000 kcal.

The general characteristics of the individual participants in the baseline study are summarized in Table 1 according to the quintiles of the amount of daily energy-adjusted diet-related GHG emissions. This study included a total of 41,659 participants, of whom 30.84% were males ($n = 12,846$). High energy-adjusted diet-related GHG emissions were associated with younger participants among both sexes, those who had a higher educational level, and those who were current smokers and drinkers (all $p < 0.05$). Notably, the effects of BMI levels differed between females and males: for males, a rise in energy-adjusted diet-related GHG emissions was associated with being overweight or obese ($p = 0.0094$), whereas the opposite trend appeared for females ($p < 0.0001$).

The dietary compositions of each of the energy-adjusted GHG emissions groups according to sex are shown in Table 2. Of all the participants, the Q1 group consumed the most carbohydrates and the lowest amounts of protein and fat. In addition, the carbohydrate intake ($\sim$78% of the daily intake in the male and female Q1 groups) was higher than the KDRIs[32] (55%–65%), and the fat intake ($\sim$10% in the male and female Q1 groups) was lower (15%–30%). Meanwhile, the Q1 group had a higher aMED score (3.02 for males and 3.00 for females) than the other quintile groups. Figure S2 (Table S2) shows the percentages of daily diet-GHG emissions from each food group according to the KFBW,

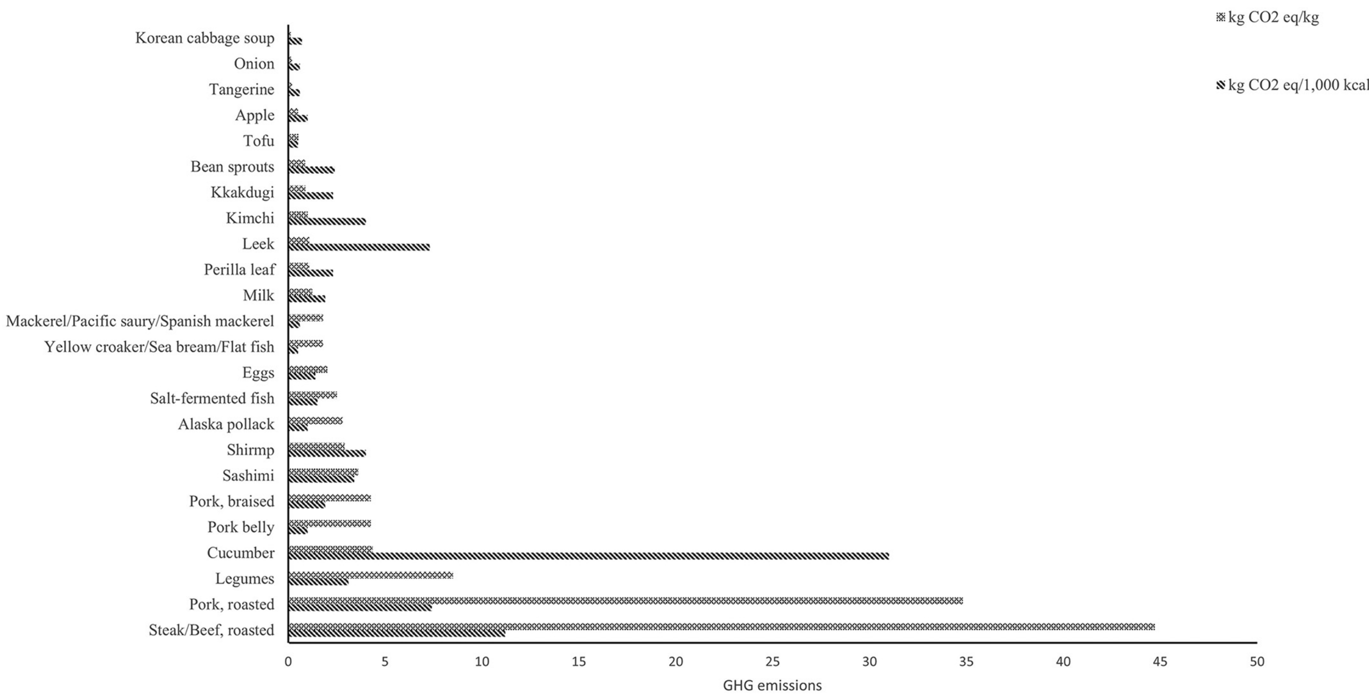

Figure 1. GHG emissions of Korea's representative food types according to the HEXA FFQ data. See Table S1 for detailed information regarding the complete HEXA diet-related GHG emissions. Note: CO_2 eq, carbon dioxide equivalents; FFQ, food frequency questionnaire; GHG emissions, greenhouse gas emissions; HEXA, Health Examinees study.

and the corresponding serving portions are shown in Figure S3 (Table S3). Notably, the main differences between the GHG emission quintiles were also found to be related to cereal and meat (beef and pork in particular) consumption. Meats like fish and poultry contributed lower proportions of GHG emissions in Q5 than in Q1, even though the percentage consumed was higher in Q5.

The associations between MetS and its components and dietary GHG emissions in the current study are shown in Table 3. The average follow-up period was 5.01 y (interquartile range: 3.9–6.1 y). Of the 12,846 male participants, 1,968 MetS cases developed during the follow-up period. However, no significant correlations between MetS and diet-related GHG emissions among males were found. A total of 3,628 MetS cases were identified among the female participants ($n = 28{,}813$). In addition, the female Q1 group had significantly lower ORs for MetS (OR = 0.824; 95% CI: 0.732, 0.928), elevated TG levels (OR = 0.895; 95% CI: 0.804, 0.996), elevated WC levels (OR = 0.868; 95% CI: 0.789, 0.954), and elevated blood pressure (OR = 0.900; 95% CI: 0.824, 0.983) in comparison with the female Q5 group.

Discussion

This study was conducted to assess the energy-adjusted GHG emissions associated with the self-selected diets of Korean adults (in accordance with information obtained from FFQs completed during the HEXA study). A low energy-adjusted GHG emission diet had a higher aMED score, which indicated a higher diet quality. In addition, the lower risk for MetS in the low energy-adjusted diet-related GHG emissions group among the female participants indicated its health benefits to some extent.

We developed a GHG emissions (CO_2 emissions) database related to the representative Korean foods that were included in HEXA FFQ data by matching the results obtained from several LCA databases obtained from previous research primarily related to Korean foods.[12,34,35,41] Although the precision of some of the data requires improvement, Table S1 shows that the ranking of GHG emissions associated with every individual food item is generally consistent with that obtained using data from other studies.[3,42,43] For the purposes of the present study, the ranking of data was more important than its precise value and aimed to obtain a general awareness of the approximate GHG emissions.

Our study shows that the constituents of daily diets with a lower climate impact in terms of GHG emissions after being standardized by 2,000 kcal had a higher modified aMED score. This finding was consistent with the findings of some previous review studies, which reported that the Mediterranean diet exhibited relatively low environmental effects.[20,44,45] Another previous cohort study has illustrated the potential co-benefits that can be obtained for health and climate if the population shifts to a low-meat diet after comparing six different diet patterns among French participants, from lactovegetarians to diets with high meat content.[46] They defined a low-meat diet as a diet with a total meat intake of <50 g/d.[46] In the current study, the serving size of red meat was 150 g, and the serving size of fish was 40 g per the KDRIs. The distribution of meat and fish intake in Table 2 indicates that participants in Q1 could also be classified as having a low-meat diet, which is nutritionally adequate and climate-friendly. A previous cross-sectional epidemiological study focused on self-selected diets also demonstrated that diets with a higher U.S. Healthy Eating Index (rather than Med) score had lower GHG emissions per 1,000 kcal and contained more fiber, poultry, plant protein foods, and less meat.[47]

In the present study, although there was little difference in the absolute consumption of fish and poultry among different quintiles, the area distribution of the pie chart (Figure S2) suggested that fish and poultry charged more in the total meat consumption in Q1 group. It meant that participants who recorded an increase in the meat consumption percentage of fish and poultry were found to have a lower risk of developing MetS (Figure S2; Table 3), and the production of such food items involved lower GHG emissions. In addition, diets rich in fish and poultry were found to be associated with lower or equivalent GHG emission

Table 1. Baseline general characteristics of the study participants from the Health Examinees study according to the quintiles of the energy-adjusted diet-related GHG emissions ($n = 41,659$).

	Energy-adjusted dietary GHG emissions					
	Q1	Q2	Q3	Q4	Q5	p-Value[a]
Males						
$n = 12,846$	2,569	2,569	2,570	2,569	2,569	—
GHG emissions (kg of CO_2 eq/d)	1.74 ± 0.01^{a}	2.23 ± 0.01^{b}	2.67 ± 0.02^{c}	3.26 ± 0.02^{d}	4.81 ± 0.04^{e}	<0.0001
Age (y)	55.28 ± 0.16^{a}	55.09 ± 0.17^{a}	54.26 ± 0.17^{b}	53.68 ± 0.17^{c}	53.59 ± 0.17^{c}	<0.0001
BMI (kg/m^2)	23.66 ± 0.05^{b}	$23.79 \pm 0.05^{a,b}$	$23.75 \pm 0.05^{a,b}$	23.88 ± 0.05^{a}	23.86 ± 0.05^{a}	0.0094
<18.5	57 (2.22%)	34 (1.32%)	40 (1.56%)	38 (1.48%)	44 (1.72%)	0.0008
≥18.5 and <25	1,743 (67.87%)	1,771 (68.94%)	1,752 (68.17%)	1,687 (65.67%)	1,677 (65.41%)	—
≥25 and <30	740 (28.82%)	723 (28.14%)	762 (29.65%)	815 (31.72%)	802 (31.28%)	—
≥30	28 (1.09%)	41 (1.60%)	16 (0.62%)	29 (1.13%)	41 (1.60%)	—
Smoking status [n (%)]	—	—	—	—	—	<0.0001
Never	926 (36.05%)	873 (33.98%)	823 (32.02%)	791 (30.79%)	811 (31.57%)	—
Past smokers	1,058 (41.18%)	1,069 (41.61%)	1,075 (41.83%)	1,064 (41.42%)	974 (37.91%)	—
Current smokers	578 (22.50%)	619 (24.09%)	660 (25.68%)	705 (27.44%)	776 (30.21%)	—
Missing	7 (0.27%)	8 (0.31%)	12 (0.47%)	9 (0.35%)	8 (0.31%)	—
Drinking status [n (%)]	—	—	—	—	—	<0.0001
Never an alcohol drinker	891 (34.68%)	773 (30.09%)	664 (25.84%)	603 (23.47%)	589 (22.93%)	—
Current alcohol drinker	1,671 (65.04%)	1,789 (69.64%)	1,899 (73.89%)	1,956 (76.14%)	1,972 (76.76%)	—
Missing	7 (0.27%)	7 (0.27%)	7 (0.27%)	10 (0.39%)	8 (0.31%)	—
Educational level [n (%)]	—	—	—	—	—	<0.0001
Under middle school	669 (26.04%)	602 (23.43%)	452 (17.59%)	476 (18.53%)	464 (18.06%)	—
High school	998 (38.85%)	1,003 (39.04%)	1,072 (41.71%)	986 (38.38%)	990 (38.54%)	—
College or above	873 (33.98%)	938 (36.51%)	1,014 (39.46%)	1,086 (42.27%)	1,090 (42.43%)	—
Missing	29 (1.13%)	26 (1.01%)	32 (1.25%)	21 (0.82%)	25 (0.97%)	—
Physical activity level [n (%)]	—	—	—	—	—	0.0003
Inactive	2,015 (78.44%)	1,975 (76.88%)	1,946 (75.72%)	1,971 (76.72%)	2,004 (78.01%)	—
Active	500 (19.46%)	533 (20.75%)	535 (20.82%)	508 (19.77%)	464 (18.06%)	—
Missing	54 (2.10%)	61 (2.37%)	89 (3.46%)	90 (3.50%)	101 (3.93%)	—
MetS biomarkers						
TG (mg/dL)	118.01 ± 1.45^{b}	121.20 ± 1.54^{b}	121.50 ± 1.35^{b}	121.83 ± 1.42^{b}	126.26 ± 1.55^{a}	0.0028
WC (cm)	83.42 ± 0.13^{b}	83.70 ± 0.13^{b}	83.66 ± 0.13^{b}	$83.82 \pm 0.13^{a,b}$	84.11 ± 0.14^{a}	0.0063
HDL-C (mg/dL)	$50.98 \pm 0.23^{b,c}$	50.81 ± 0.22^{c}	$51.38 \pm 0.22^{b,c}$	$51.62 \pm 0.22^{a,b}$	52.23 ± 0.23^{a}	<0.0001
FPG (mg/dL)	93.19 ± 0.28^{a}	92.41 ± 0.26^{b}	$92.49 \pm 0.25^{a,b}$	92.38 ± 0.24^{b}	$92.72 \pm 0.23^{a,b}$	0.1354
DBP (mmHg)	77.68 ± 0.18^{a}	77.00 ± 0.18^{b}	77.10 ± 0.18^{b}	77.10 ± 0.18^{b}	77.13 ± 0.18^{b}	0.0654
SBP (mmHg)	123.71 ± 0.28^{a}	$122.99 \pm 0.27^{a,b}$	122.90 ± 0.26^{b}	122.57 ± 0.26^{b}	122.70 ± 0.26^{b}	0.0266
Females						
$n = 28,813$	5,762	5,763	5,763	5,763	5,762	—
GHG emission (kg of CO_2 eq/d)	1.64 ± 0.01^{a}	2.08 ± 0.01^{b}	2.43 ± 0.01^{c}	2.92 ± 0.01^{d}	4.21 ± 0.02^{e}	<0.0001
Age (y)	52.61 ± 0.10^{a}	51.85 ± 0.10^{b}	51.32 ± 0.10^{c}	50.85 ± 0.10^{d}	50.49 ± 0.10^{e}	<0.0001
BMI (kg/m^2)	23.11 ± 0.03^{a}	$23.06 \pm 0.03^{a,b}$	$23.01 \pm 0.03^{b,c}$	22.94 ± 0.03^{c}	22.81 ± 0.03^{d}	<0.0001
<18.5	151 (2.62%)	158 (2.74%)	149 (2.59%)	140 (2.43%)	173 (3.00%)	0.0113
≥18.5 and <25	4,239 (73.62%)	4,301 (74.66%)	4,338 (75.30%)	4,370 (75.84%)	4,381 (76.06%)	—
≥25 and <30	1,261 (21.90%)	1,201 (20.85%)	1,187 (20.60%)	1,140 (19.78%)	1,131 (19.64%)	—
≥30	107 (1.86%)	101 (1.75%)	87 (1.51%)	112 (1.94%)	75 (1.30%)	—
Smoking status [n (%)]	—	—	—	—	—	0.0003
Never	5,601 (97.21%)	5,605 (97.26%)	5,604 (97.24%)	5,610 (97.35%)	5,526 (95.90%)	—
Past smokers	50 (0.87%)	50 (0.87%)	52 (0.90%)	46 (0.80%)	78 (1.35%)	—
Current smokers	84 (1.46%)	77 (1.34%)	78 (1.35%)	83 (1.44%)	130 (2.26%)	—
Missing	27 (0.47%)	31 (0.54%)	29 (0.50%)	24 (0.42%)	28 (0.49%)	—
Drinking status [n (%)]	—	—	—	—	—	<0.0001
Never an alcohol drinker	4,228 (73.38%)	4,025 (69.84%)	3,838 (66.60%)	3,784 (65.66%)	3,598 (62.44%)	—
Current alcohol drinker	1,504 (26.10%)	1,712 (29.71%)	1,896 (32.90%)	1,954 (33.91%)	2,136 (37.07%)	—
Missing	30 (0.52%)	26 (0.45%)	29 (0.50%)	25 (0.43%)	28 (0.49%)	—
Educational level [n (%)]	—	—	—	—	—	<0.0001
Under middle school	2,427 (42.12%)	1,908 (33.11%)	1,679 (29.13%)	1,470 (25.51%)	1,317 (22.86%)	—
High school	2,326 (40.37%)	2,685 (46.59%)	2,731 (47.39%)	2,773 (48.12%)	2,811 (48.79%)	—
College or above	943 (16.37%)	1,103 (19.14%)	1,293 (22.44%)	1,459 (25.32%)	1,585 (27.51%)	—
Missing	66 (1.15%)	67 (1.16%)	60 (1.04%)	61 (1.06%)	49 (0.85%)	—
Physical activity level [n (%)]	—	—	—	—	—	0.0005
Inactive	4,677 (81.17%)	4,565 (79.21%)	4,613 (80.05%)	4,539 (78.76%)	4,557 (79.09%)	—
Active	982 (17.04%)	1,067 (18.51%)	1,010 (17.53%)	1,062 (18.43%)	1,034 (17.95%)	—
Missing	103 (1.79%)	131 (2.27%)	140 (2.43%)	162 (2.81%)	171 (2.97%)	—
MetS biomarkers						
TG (mg/dL)	93.86 ± 0.61^{a}	94.01 ± 0.63^{a}	93.15 ± 0.66^{a}	92.62 ± 0.63^{a}	93.04 ± 0.67^{a}	0.5028
WC (cm)	76.66 ± 0.10^{a}	76.43 ± 0.10^{a}	76.46 ± 0.10^{a}	75.98 ± 0.10^{b}	75.86 ± 0.10^{b}	<0.0001
HDL-C (mg/dL)	57.62 ± 0.16^{d}	58.20 ± 0.16^{c}	$58.63 \pm 0.16^{b,c}$	$58.92 \pm 0.16^{a,b}$	59.15 ± 0.17^{a}	<0.0001
FPG (mg/dL)	88.61 ± 0.14^{a}	88.57 ± 0.13^{a}	88.67 ± 0.14^{a}	88.33 ± 0.13^{a}	88.44 ± 0.12^{a}	0.3624
DBP (mmHg)	73.84 ± 0.12^{a}	73.24 ± 0.12^{b}	72.88 ± 0.12^{c}	$72.75 \pm 0.12^{c,d}$	72.49 ± 0.12^{d}	<0.0001
SBP (mmHg)	118.94 ± 0.19^{a}	118.05 ± 0.18^{b}	117.28 ± 0.18^{c}	116.84 ± 0.18^{c}	116.28 ± 0.17^{d}	<0.0001

Note: —, no data; BMI, body mass index; DBP, diastolic blood pressure; eq, equivalent; FPG, fasting plasma glucose; GHG, greenhouse gas; HDL-C, high-density lipoprotein cholesterol; MetS, metabolic syndrome; Q, quintile; SBP, systolic blood pressure; TG, triglycerides; WC, waist circumference.

[a] p-Values comparing continuous variables (presented as the mean ± standard error) were calculated using generalized linear models, and the p-values for categorical variables presented as n (%) were calculated using a chi-square test. A post hoc test was performed by a Duncan test, and the mean values with the same letters (shown as '*a*', '*b*', '*c*', '*d*', or '*e*') in each row were not significantly different.

Table 2. Distribution of macronutrients and aMED components of daily diets at baseline according to the energy-adjusted GHG emissions among 41,659 participants in the Health Examinees study, South Korea.

	Energy-adjusted diet-related GHG emissions					
	Q1	Q2	Q3	Q4	Q5	p-Value
Males ($n = 12{,}846$)	2,569	2,569	2,570	2,569	2,569	—
Total energy (kcal/d)	$1{,}587.14 \pm 7.31^{e}$	$1{,}746.57 \pm 8.09^{d}$	$1{,}825.53 \pm 8.41^{c}$	$1{,}903.35 \pm 9.07^{b}$	$2{,}028.44 \pm 10.38^{a}$	<0.0001
Protein (g/d)	46.57 ± 0.27^{e}	54.82 ± 0.31^{d}	60.14 ± 0.33^{c}	66.47 ± 0.37^{b}	80.20 ± 0.50^{a}	<0.0001
Energy percentage (%)	11.68 ± 0.04^{e}	12.53 ± 0.04^{d}	13.16 ± 0.04^{c}	13.96 ± 0.04^{b}	15.77 ± 0.05^{a}	<0.0001
Fat (g/d)	18.43 ± 0.18^{e}	24.31 ± 0.21^{d}	28.14 ± 0.22^{c}	33.22 ± 0.25^{b}	43.76 ± 0.34^{a}	<0.0001
Energy percentage (%)	10.20 ± 0.07^{e}	12.32 ± 0.07^{d}	13.72 ± 0.07^{c}	15.54 ± 0.07^{b}	19.21 ± 0.09^{a}	<0.0001
Carbohydrate (g/d)	308.75 ± 1.37^{c}	327.12 ± 1.48^{b}	332.92 ± 1.52^{a}	334.62 ± 1.57^{a}	328.45 ± 1.69^{b}	<0.0001
Energy percentage (%)	78.12 ± 0.10^{a}	75.15 ± 0.10^{b}	73.13 ± 0.10^{c}	70.50 ± 0.10^{d}	65.02 ± 0.13^{e}	<0.0001
aMED	3.02 ± 0.03^{a}	2.84 ± 0.03^{b}	2.91 ± 0.03^{b}	2.89 ± 0.03^{b}	3.00 ± 0.03^{a}	<0.0001
Vegetables (servings/d)	2.40 ± 0.04^{e}	3.12 ± 0.04^{d}	3.59 ± 0.05^{c}	4.03 ± 0.05^{b}	4.60 ± 0.06^{a}	<0.0001
Legumes (servings/d)	1.02 ± 0.02^{c}	1.19 ± 0.02^{b}	$1.22 \pm 0.02^{a,b}$	$1.25 \pm 0.02^{a,b}$	1.28 ± 0.02^{a}	<0.0001
Fruits (servings/d)	0.93 ± 0.02^{d}	1.19 ± 0.02^{c}	1.27 ± 0.02^{b}	1.35 ± 0.02^{a}	1.38 ± 0.02^{a}	<0.0001
Whole grain (servings/d)	3.10 ± 0.02^{a}	3.02 ± 0.02^{b}	2.95 ± 0.02^{c}	2.82 ± 0.02^{d}	2.63 ± 0.02^{e}	<0.0001
Red and processed meat (servings/d)	0.16 ± 0.00^{e}	0.27 ± 0.00^{d}	0.40 ± 0.01^{c}	0.60 ± 0.01^{b}	1.24 ± 0.02^{a}	<0.0001
Fish (servings/d)	0.60 ± 0.01^{e}	0.75 ± 0.01^{d}	0.83 ± 0.01^{c}	0.92 ± 0.01^{b}	1.08 ± 0.02^{a}	<0.0001
Monounsaturated fatty acids/saturated fatty acids	0.79 ± 0.00^{d}	0.78 ± 0.00^{d}	0.80 ± 0.00^{c}	0.83 ± 0.00^{b}	0.89 ± 0.00^{a}	<0.0001
Alcohol (g/d)	$19.10 \pm 0.63^{c,d}$	18.65 ± 0.58^{d}	$20.51 \pm 0.63^{b,c}$	21.36 ± 0.56^{b}	24.51 ± 0.69^{a}	<0.0001
Females ($n = 28{,}813$)	5,762	5,763	5,763	5,763	5,762	—
Total energy (kcal/d)	$1{,}503.51 \pm 5.32^{e}$	$1{,}641.09 \pm 5.76^{d}$	$1{,}690.44 \pm 6.14^{c}$	$1{,}740.04 \pm 6.68^{b}$	$1{,}813.49 \pm 7.37^{a}$	<0.0001
Protein (g/d)	44.29 ± 0.19^{e}	52.08 ± 0.21^{d}	56.49 ± 0.24^{c}	61.85 ± 0.28^{b}	71.72 ± 0.34^{a}	<0.0001
Energy percentage (%)	11.77 ± 0.03^{e}	12.70 ± 0.03^{d}	13.35 ± 0.03^{c}	14.19 ± 0.03^{b}	15.81 ± 0.03^{a}	<0.0001
Fat (g/d)	16.79 ± 0.13^{e}	22.35 ± 0.14^{d}	25.81 ± 0.16^{c}	29.99 ± 0.17^{b}	38.06 ± 0.22^{a}	<0.0001
Energy percentage (%)	9.81 ± 0.05^{e}	12.10 ± 0.05^{d}	13.57 ± 0.05^{c}	15.35 ± 0.05^{b}	18.76 ± 0.07^{a}	<0.0001
Carbohydrate (g/d)	293.80 ± 1.02^{b}	307.91 ± 1.08^{a}	308.04 ± 1.11^{a}	305.69 ± 1.17^{a}	296.01 ± 1.23^{b}	<0.0001
Energy percentage (%)	78.42 ± 0.07^{a}	75.20 ± 0.07^{b}	73.07 ± 0.07^{c}	70.45 ± 0.07^{d}	65.42 ± 0.09^{e}	<0.0001
aMED	3.00 ± 0.02^{d}	2.79 ± 0.02^{b}	3.00 ± 0.02^{a}	3.00 ± 0.02^{a}	2.95 ± 0.02^{c}	<0.0001
Vegetables (servings/d)	2.83 ± 0.03^{e}	3.61 ± 0.03^{d}	4.15 ± 0.04^{c}	4.75 ± 0.04^{b}	5.34 ± 0.05^{a}	<0.0001
Legumes (servings/d)	1.01 ± 0.01^{c}	1.23 ± 0.02^{b}	$1.27 \pm 0.02^{a,b}$	1.30 ± 0.02^{a}	1.25 ± 0.02^{b}	<0.0001
Fruits (servings/d)	1.36 ± 0.02^{d}	1.66 ± 0.02^{c}	1.77 ± 0.02^{b}	1.87 ± 0.02^{a}	$1.82 \pm 0.02^{a,b}$	<0.0001
Whole grain (servings/d)	2.80 ± 0.01^{a}	2.66 ± 0.01^{b}	2.52 ± 0.01^{c}	2.35 ± 0.01^{d}	2.14 ± 0.01^{e}	<0.0001
Red and processed meat (servings/d)	0.12 ± 0.00^{e}	0.20 ± 0.00^{d}	0.30 ± 0.00^{c}	0.45 ± 0.00^{b}	0.90 ± 0.01^{a}	<0.0001
Fish (servings/d)	0.65 ± 0.01^{e}	0.82 ± 0.01^{d}	0.90 ± 0.01^{c}	1.02 ± 0.01^{b}	1.14 ± 0.01^{a}	<0.0001
Monounsaturated fatty acids/saturated fatty acids	0.79 ± 0.00^{c}	0.78 ± 0.00^{d}	$0.79 \pm 0.00^{c,d}$	0.81 ± 0.00^{b}	0.87 ± 0.00^{a}	<0.0001
Alcohol (g/d)	5.02 ± 0.25^{b}	4.80 ± 0.21^{b}	4.85 ± 0.18^{b}	5.46 ± 0.24^{b}	6.47 ± 0.25^{a}	<0.0001

Note: —, no data; aMED, alternative Mediterranean Diet score; eq, equivalent; GHG emissions, greenhouse gas emissions; KDRI, Korea Dietary Recommendation Index; Q, quintile.

[a]*p*-Values comparing continuous variables (presented as the mean ± standard error) were calculated using generalized linear models, and the *p*-values for categorical variables presented as *n* (%) were calculated using a chi-square test. A post hoc test was performed by a Duncan test, and the mean values with the same letters (shown as '*a*', '*b*', '*c*', '*d*', or '*e*') in each row were not significantly different.

percentages than diets in which fish and poultry were not consumed in large quantities (Figure S2). We noted this consistency between our result and previous review research findings.[48] Therefore, fish and poultry could be considered climate-friendly food items when assuming that the total energy intake was standardized. We also found that increased vegetable intake provided an energy equivalent to that of fish or poultry but was associated with higher dietary GHG emissions. This finding differs from that of a previous cohort[3] or survey studies,[14,22] which indicates that restricting or excluding animal-based foods results in much lower GHG emissions. It is considered that the differences are mainly related to discrepancies between the primary measures of emissions in each case because the current study mainly focused on energy-adjusted diet-related GHG emissions and prior studies estimated absolute GHG emissions without considering the energy intake imbalance which could impact the health outcome. Although the present study found that the GHG emissions associated with beef were relatively higher than those of other foods, the method used to cook the beef (Table S1) and its origin (from abroad or local) can have an effect on the GHG emissions.[48] Therefore, changes to the cooking method and origin (imported beef or local beef) selection should be considered to improve the associated nutritional intake and diet-related effects on GHG emissions.

In the current analysis, the low energy-adjusted diet-related GHG emissions group (Q1 or Q2) exhibited a lower OR for MetS or its five components compared with the Q5 group. Moreover, these groups had a higher aMED score. Consistent with this, a previous cross-sectional study[49] and meta-analyses[50] have reported that adhering to a Mediterranean diet (higher MED score) reduced the risk for MetS and its components. In the current study, the optimal diet pattern included higher carbohydrates, lower fat contents, and more fish consumption, which is rich in polyunsaturated fatty acids (PUFAs; i.e., omega-3 fatty acids), than red meat. This pattern is also consistent with a previous clinical intervention study that indicated that a high-carbohydrate, low-fat diet supplemented with omega-3 PUFA was negatively correlated with MetS,[51] with the associated mechanism being considered to mainly resulting from the types of carbohydrates and unsaturated fatty acids ingested.[52] Overall, energy-restricted diets have generally been considered an effective strategy to manage MetS.[53–55] Our results also support this approach because the Q1 and Q2 groups had lower total energy intakes and exhibited lower risks for MetS and its components (Table 3).

The Mediterranean diet is a high-quality dietary regimen that has become well-known owing to its optimal nutrient profile.[56] The results of our analysis revealed that higher aMED scores were associated with significantly lower intakes of red and

Table 3. Adjusted ORs for MetS and its components at follow-up, according to the baseline daily energy-adjusted diet-related GHG emissions among 41,659 participants in the Health Examinees study, South Korea.

	Energy-adjusted diet-related GHG emissions					p-Value for trend
	Q1	Q2	Q3	Q4	Q5	
Males ($n = 12,846$)						
n/person-years	2,569/13,385.1	2,569/12,815.8	2,570/12,716.2	2,569/12,405.1	2,569/12,280.9	—
MetS	378 (14.71%)	402 (15.65%)	390 (15.18%)	392 (15.26%)	406 (15.80%)	0.8349
	0.984 (0.832, 1.165)	1.035 (0.880, 1.216)	1.005 (0.857, 1.180)	0.954 (0.814, 1.119)	Ref	0.8528
TG ≥150 mg/dL	605 (23.55%)	610 (23.74%)	644 (25.06%)	622 (24.21%)	699 (27.21%)	0.0156
	0.903 (0.788, 1.034)	0.889 (0.779, 1.015)	0.937 (0.823, 1.066)	0.851 (0.748, 0.969)	Ref	0.1573
HDL-C <40 mg/dL	285 (11.09%)	283 (11.02%)	230 (8.95%)	228 (8.88%)	237 (9.23%)	0.0055
	1.160 (0.956, 1.408)	1.184 (0.981, 1.428)	0.974 (0.802, 1.182)	0.958 (0.790, 1.162)	Ref	0.0470
WC ≥90 cm	491 (19.11%)	512 (19.93%)	512 (19.92%)	558 (21.72%)	552 (21.49%)	0.0937
	0.907 (0.766, 1.074)	0.931 (0.791, 1.096)	0.971 (0.827, 1.139)	1.022 (0.873, 1.196)	Ref	0.1878
FPG ≥100 mg/dL	1,020 (39.70%)	972 (37.84%)	1,015 (39.49%)	997 (38.81%)	1,010 (39.31%)	0.6620
	1.022 (0.907, 1.152)	0.938 (0.835, 1.054)	1.007 (0.898, 1.130)	0.973 (0.868, 1.090)	Ref	0.9616
BP	1,012 (39.39%)	1,022 (39.78%)	1,010 (39.30%)	976 (37.99%)	1,001 (38.96%)	0.7390
≥130/85 mmHg	0.991 (0.878, 1.117)	1.004 (0.894, 1.128)	1.000 (0.891, 1.122)	0.947 (0.844, 1.062)	Ref	0.8818
Females ($n = 28,813$)						
n/person-years	5,762/30,272.6	5,763/29,340.8	5,763/28,851.1	5,763/28,798.2	5,762/27,696.6	
MetS	737 (12.79%)	757 (13.14%)	724 (12.56%)	702 (12.18%)	708 (12.29%)	0.5367
	0.824 (0.732, 0.928)	0.920 (0.819, 1.033)	0.919 (0.818, 1.032)	0.916 (0.815, 1.029)	Ref	0.0043
TG ≥150 mg/dL	844 (14.65%)	809 (14.04%)	866 (15.03%)	864 (14.99%)	850 (14.75%)	0.5707
	0.895 (0.804, 0.996)	0.880 (0.791, 0.978)	0.976 (0.880, 1.083)	0.992 (0.895, 1.100)	Ref	0.0094
HDL-C <50 mg/dL	1,108 (19.23%)	1,064 (18.46%)	1,012 (17.56%)	996 (17.28%)	994 (17.25%)	0.0199
	1.047 (0.949, 1.155)	1.024 (0.930, 1.128)	0.983 (0.892, 1.083)	0.978 (0.888, 1.078)	Ref	0.3191
WC ≥80 cm	2,132 (37.00%)	2,124 (36.86%)	2,128 (36.93%)	2,017 (35.00%)	1,999 (34.69%)	0.0107
	0.868 (0.789, 0.954)	0.933 (0.850, 1.024)	1.001 (0.913, 1.098)	0.939 (0.856, 1.031)	Ref	0.0115
FPG ≥100 mg/dL	1,297 (22.51%)	1,261 (21.88%)	1,237 (21.46%)	1,203 (20.87%)	1,237 (21.47%)	0.2911
	0.925 (0.844, 1.015)	0.933 (0.852, 1.022)	0.937 (0.856, 1.026)	0.926 (0.846, 1.015)	Ref	0.1012
BP	1,543 (26.78%)	1,560 (27.07%)	1,489 (25.84%)	1,437 (24.93%)	1,458 (25.30%)	0.0376
≥130/85 mmHg	0.900 (0.824, 0.983)	0.971 (0.891, 1.059)	0.948 (0.869, 1.033)	0.932 (0.855, 1.016)	Ref	0.0712

Note: Cases and incidences are presented by n (%). p-Values were calculated using a chi-square test. The adjusted ORs are presented as OR (95% CI) and were calculated using a multivariate logistic regression model by adjusting for age, educational level, drinking status, smoking status, physical activity, BMI, and total energy intake. The p-value for trend was based on a linear regression with a median value of diet-related GHG emissions in each quintile treated as a group linear variable. Among males, the ranges of energy-adjusted GHG emission were 0.66–2.15, 2.15–2.55, 2.55–2.97, 2.97–3.61, and 3.61–11.05 kg of CO_2 eq/d/2,000 kcal, respectively. Among females, these ranges were 0.66–2.14, 2.14–2.53, 2.53–2.93, 2.93–3.54, and 3.54–17.44, respectively. MetS cases were those that met three or more of the ATP III criteria. —, no data; BMI, body mass index; BP, blood pressure; CI, confidence interval; eq, equivalent; FPG, fasting plasma glucose; HDL-C, high-density lipoprotein cholesterol; MetS, metabolic syndrome; OR, odds ratio; Ref, reference; TG, triglyceride; WC, waist circumference.

processed meat in comparison with the lower aMED scoring group. Specifically, higher aMED scores reflect higher intakes of vegetables, legumes, fruits, whole grains, and fish; lower intakes of red and processed meat; and moderate intakes of alcohol. Among these, fish constitutes a good source of PUFAs, and vegetables and fruits are abundant in antioxidants and bioactive compounds, with whole grains, vegetables, and legumes being primarily low-fat, high-fiber foods.

Furthermore, our results show that the low-GHG emission group with higher aMED scores had a lower risk for increased WC, elevated blood pressure, and elevated TG levels among females. The mechanism by which the Mediterranean diet protects against increased WC may involve the ability of its high dietary fiber content to induce satiety and lower energy intake.[57] In addition, the whole grains and legumes in the Mediterranean diet constitute good sources of low glycemic index carbohydrates,[58] which are useful in lowering postprandial plasma glucose excursions.[59] Low-fat diets or diets enriched with monounsaturated fatty acids and PUFAs have also been proposed as a beneficial method to improve serum TG levels based on the results of a randomized controlled study.[60]

However, the present study has several limitations. First, the diet-related GHG emission database was established based on a review of previous literature, and the contents may not be entirely accurate because no correspondence existed between the different studies for all the data on the individual food items. Nevertheless, the database is considered sufficient because the approximate values of the food-group level GHG emissions agree with those of previous epidemiological studies.[12,43] Second, unlike analyses of all-cause mortality, the exact time of MetS onset is unknown, so this study could not consider the time effect and perform a sensitive analysis by excluding participants who met the MetS criteria shortly after the baseline survey. Further limitations result from a reliance on the results of the FFQs, which may contain biases, because these may be over- or under-reported. However, the reliability and validity of this study have been determined by means of a 24-h recall by other research,[28] and the missing data have been accommodated by the HEXA study group using an imputation method. The dietary data from the HEXA Study are suitable for analysis in a nutritional epidemiological study. In addition, the survey focused on middle-age and elderly participants, whose dietary activity was not readily changed except for purposes of disease control. Finally, the study only focused on GHG emissions, whereas it is recognized that additional aspects contribute to the food environmental impact, including water eutrophication. In particular, owing to the inclusion of increased amounts of seafood in the Mediterranean diet, the issue of water eutrophication was more serious than that observed with a solely vegetarian diet.[61] Thus, caution should be observed when making dietary suggestions. In our adjusted model, we replaced the missing covariates by using some methods that have been commonly accepted in epidemiological studies, but the bias still could appear under some situations. However, because the number of participants with missing covariates is 1,634 (3.9% of participants), we believe that any bias due to the missingness would not be enough to impact the association between exposure and outcome.[62,63] Despite these limitations, we believe that this study provides novel and important results because it quantitatively examines the environmental and health implications of daily diet patterns in Korea by linking food-level variables with a large population sample.

Conclusions

The results, based on energy-adjusted GHG emissions, indicate that self-selected diets with low energy-adjusted GHG emissions have higher aMED scores and lower risks for MetS. In addition, consuming diets in accordance with the guidelines from the aMED or the Korean Food Balance Wheel is beneficial for an individual's health and the environment. Future associated research should consider other environmental indexes, like water footprint or land use, and assess them using more appropriate tools.

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L.-J.T. conceptualized the study and conducted the methodology, formal analysis, and original draft preparation, review, and editing. S.S. performed review and editing, supervision, and project administration. Both authors critically reviewed and approved the final manuscript.

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The data sets presented in this article are not readily available because they are from the National Genome Research Institute, Korea Centers for Disease Control and Prevention. Restrictions apply to the availability of these data, which were used under license for this study. Data described in the manuscript, codebook, and analytic code are available from the authors with the permission of the National Genome Research Institute, Korea Centers for Disease Control and Prevention. Requests to access the data sets should be directed to the National Genome Research Institute, Korea Centers for Disease Control and Prevention: https://kdca.go.kr/contents.es?mid=a40504060300.

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