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Ultra-processed foods consumption as a promoting factor of greenhouse gas emissions, water, energy, and land use: A longitudinal assessment

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Abbreviations: UPF, Ultra-processed Foods; Mets, Metabolic Syndrome; MedDiet, The Mediterranean Diet; LCA, Life Cycle Assessment; GHGs, Greenhouse gas emissions; BMI, Body mass index; FFQ, Food frequency questionnaire; PA, Physical activity; CO2eq, Carbon Dioxide equivalent; m3, Cubic meters; MJ, Megajoules; Pt, points of land use; T1, Tertile 1; T2, Tertile 2; T3, Tertile 3; SD, Standard deviation; GLM, General Linear Model; METs, Metabolic equivalents of task; FAO, Food and Agriculture Organization.

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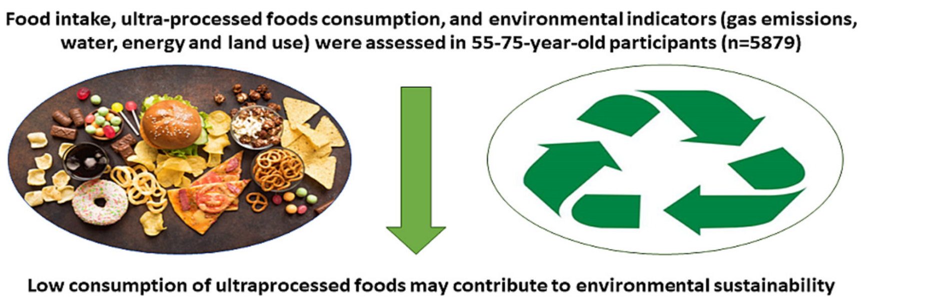
HIGHLIGHTS

- Decreasing consumption of ultra-processed foods may improve environmental sustainability.
- The lower ultra-processed food dietary contents, the lower the environmental footprints of the diet consumed.
- Decreasing ultra-processed food consumption should be considered for health and for environmental protection.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Dietary patterns can produce an environmental impact. Changes in people's diet, such as the increased consumption of ultra-processed food (UPF) can not only influence human health but also environment sustainability.
Objectives: Assessment of the impact of 2-year changes in UPF consumption on greenhouse gas emissions and water, energy and land use.
Design: A 2-year longitudinal study after a dietary intervention including 5879 participants from a Southern European population between the ages of 55–75 years with metabolic syndrome.
Methods: Food intake was assessed using a validated 143-item food frequency questionnaire, which allowed classifying foods according to the NOVA system. In addition, sociodemographic data, Mediterranean diet adherence, and physical activity were obtained from validated questionnaires. Greenhouse gas emissions, water, energy and land use were calculated by means of the Agribalyse® 3.0.1 database of environmental impact indicators for food items. Changes in UPF consumption during a 2-year period were analyzed. Statistical analyses were conducted using computed General Linear Models.
Results: Participants with major reductions in their UPF consumption reduced their impact by −0.6 kg of CO_2eq and −5.3 MJ of energy. Water use was the only factor that increased as the percentage of UPF was reduced.
Conclusions: Low consumption of ultra-processed foods may contribute to environmental sustainability. The processing level of the consumed food should be considered not only for nutritional advice on health but also for environmental protection.
Trial registration: ISRCTN, ISRCTN89898870. Registered 05 September 2013, http://www.isrctn.com/ISRCTN89898870.

1. Introduction

Ultra-processed foods (UPF) are defined as industrial products produced from substances obtained from food or synthesized from other organic sources. They usually contain little or none of the primary food, are ready to eat or heat, and are high in additives, including fat, salt, or sugar (Talens et al., 2020). Different factors such as eating in fast-food restaurants (Souza et al., 2021), economic and social development of a region, food system industrialization, technological change and globalization may be also affecting the increase of UPF consumption and deteriorating the diet both in developed and developing countries (Baker et al., 2020; Monteiro et al., 2013).

Higher consumption of UPF could have harmful effects a population's health, increasing the risk of overweight and obesity, cardiovascular diseases, type 2-diabetes, cancer, metabolic syndrome (MetS) and other non-communicable diseases (Talens et al., 2020; Poti et al., 2017). Further evidence is required to understand the mechanisms by which UPFs impact health, beyond nutrient-based interactions (Poti et al., 2017).

Changing the diet to a less processed one could be helpful for health but also for environmental sustainability. UPF are unnecessary foods that should not be present in a balanced diet, and promote overconsumption, which is one of the main reasons for the increasing negative environmental impact (Anastasiou et al., 2022a; Anastasiou et al., 2022b). UPF production is also a primary driver off environmental pressures (Anastasiou et al., 2022a; Anastasiou et al., 2022b; da Silva et al., 2021; Garzillo et al., 2022; Kesse-Guyot et al., 2023). Each life cycle assessment (LCA) stage of UPF production contributes in a different way to the negative environmental impact, which is characterized by extensive monoculture crops, high energy demands for processing, a long transport chain and excessive packaging (Anastasiou et al., 2022b). One study found that the final LCA stages such creating the final product and packaging were the greatest environmental impact contributors in UPF-rich diets (Kesse-Guyot et al., 2023). Climate change, air pollution, biodiversity loss, land use, energy use, water use, and food wastage are the environmental parameters used to measure UPF's sustainability, they are all interconnected and negatively affected by the ultra-processed food system (Anastasiou et al., 2022a;

Anastasiou et al., 2022b). Land use, water use, and greenhouse gas emissions (GHGs) are the largest contributors to the UPF environmental impact. Additionally, meat-based UPF products also have greater negative impacts compared to plant-based options in the case of land use (Anastasiou et al., 2022a).

The Mediterranean Diet (MedDiet) is a healthy dietary pattern, based on a high consumption of fresh fruits and vegetables, unrefined cereals, and a reduced quantity of animal products consumed, mainly red and processed meat (Macdiarmid, 2013; Serra-Majem et al., 2020), which in turn leads to a reduced environmental footprint (García et al., 2023). Food based dietary guidelines (FBDG) are including sustainable diets in their recommendations (Monteiro et al., 2015; Tapsell et al., 2016; The Nutrition Division, 2019), and the environmental consequences of food systems is a consideration in public health agendas (United Nations (UN), n.d.; Willett et al., 2019). It is worth noting that the 2015 Dietary Guidelines for the Brazilian Population (Ministry of Health of Brazil, 2015) and the 2022 Dietary Guidelines for Chile (Ministerio de Salud, Subsecretaría de Salud Pública, División de Políticas Públicas Saludables y Promoción, Departamento de Nutrición y Alimentos, 2022) specifically discuss UPFs environmental impact. However, integrating sustainability in FBDG is still a fragmented process; guidelines and a guidance for stakeholders are necessary to adequately integrate sustainability into FBDG (Mazac et al., 2021).

UPF consumption has negative health impacts, and its environmental impact must also be considered. This study aims to assess how a 2-year change in UPF consumption affects the environmental impacts of the diet.

2. Methods

2.1. Design

This study is a longitudinal, multicenter, parallel-group, randomized trial conducted on the Spanish population. The study protocol can be found elsewhere (Martínez-González et al., 2019). The trial was registered in 09/05/2013 at the International Standard Randomized Controlled Trial (ISRCT; http://www.isrctn.com/ISRCTN89898870) with number 89898870.

2.2. Participants, recruitment, and ethics

Fig. 1 shows the eligible participants flow-chart; 9677 people were contacted, of whom 6874 participants met the eligibility criteria of being men aged 55–75 years or women aged 60–75 years, with overweight or obesity (body mass index (BMI) between 27.0 and 40.0 kg/m^2) and meeting at least three criteria for the MetS according to the updated harmonized definition of the International Diabetes Federation and the American Heart Association and National Heart, Lund, and Blood Institute (Alberti et al., 2009); 995 participants were excluded for not having available food frequency questionnaire (FFQ) data on the starting year (baseline), the 2-year follow-up, or both. A final number of 5879 participants were analyzed. Informed written consent was provided by all participants and the study protocol and procedures were approved by ethical committees according to the ethical standards of the Declaration of Helsinki by all the 23 participating institutions.

2.3. Assessment of dietary intake

A validated semi-quantitative 143-item FFQ (Fernández-Ballart et al., 2010; de La Fuente-Arrillaga et al., 2010; Martin-Moreno et al., 1993) was administered by trained dietitians to assess usual dietary intakes at baseline and 2-year-follow up. FFQ included 143 food items and a regular portion size was established for each item. Consumption frequencies were registered according to an incremental scale of nine categories: Never or almost never, 1–3 times per month, once per week, 2–4 times per week, 5–6 times per week, once per day, 2–3 times per day, 4–6 times per day and more than six times per day. The reported frequencies of food consumption were converted into grams of each item intake per day, multiplying it by the weight of the regular portion size indicated using a computer program based on available information from Spanish food composition tables (Moreiras et al., 2015; Mataix et al., 2013). The results determined the amount of food items (in grams) and the energy intake (in kcal) consumed for each participant per day.

2.4. Assessment of the processed food consumed according to the NOVA system

FFQ food items were classified according to the NOVA system, which was created in 2010 by the NUPENS research group at the School of Public Health of the University of Sao Paulo, led by Prof. Carlos Monteiro. It is a system that classifies foods and beverages by their degree of processing, relegating importance to the nutrient composition it contains. It presents four established groups: NOVA 1: Un-processed or minimally processed foods; NOVA 2: Processed culinary ingredients; NOVA 3: Processed foods; and NOVA 4: Ultra-processed foods (Talens et al., 2020; Monteiro et al., 2019a). Once the groups were established, the percentage of UPF consumption was calculated at baseline and 2-year-follow up; the sum of grams from

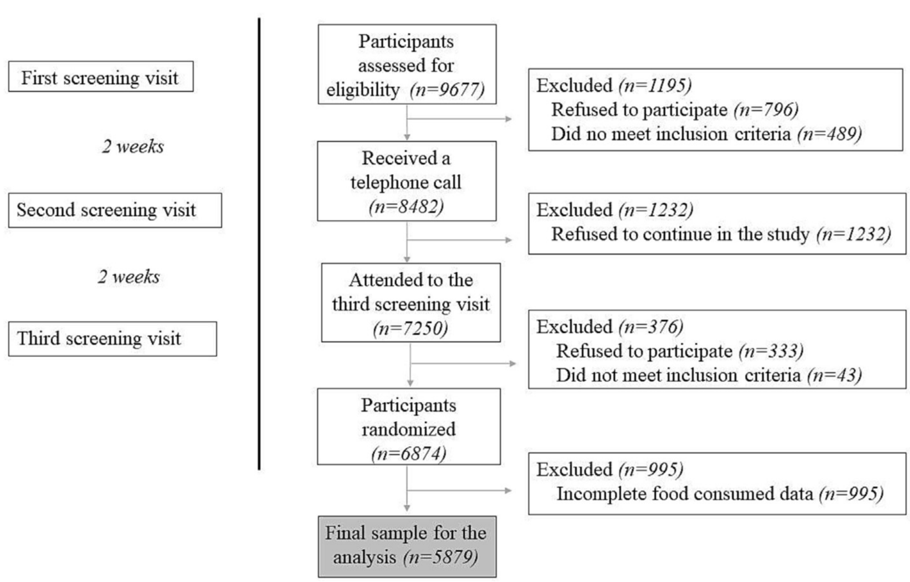

Fig. 1. Flow-chart of eligibility of participants.

UPF products consumed was divided by the total grams of all food items consumed per day, and multiplied by 100, as previously used (Konieczna et al., 2022). Differences in percentage of UPF consumption between baseline and at 2-year follow-up were distributed in tertiles: Tertile 1 (T1): Maximum %UPF reduction: $\leq -$ 37,839; Tertile 2 (T2): Medium %UPF reduction: from -3.7838 to -0.5537; Tertile 3 (T3): Minimum %UPF reduction: $\geq -$ 0.5536.

2.5. Sociodemographic characteristics and anthropometric measurements

Information related to sociodemographic characteristics such as sex, age, and educational level (primary school, secondary school, college school technician or bachelor's degree) was self-reported. Anthropometric measurements (body weight, height, waist circumference, and hip circumference) were obtained. Height was measured to the nearest millimeter, with the participant's head maintained in the Frankfurt Horizontal Plane, using a mobile stadiometer (Seca 213, SECA Deutschland, Hamburg, Germany). Weight was measured, with participants wearing light clothes and no shoes (0.6 kg of weight was subtracted for their clothing), using a Segmental Body Composition Analyzer for impedance testing (Tanita MC780P-MA, Tanita, Tokyo, Japan). BMI was calculated following the standard formula weight in kilograms divided by the square of height in meters. Waist circumference (WC) was measured halfway between the last rib and the iliac crest in duplicate with an anthropometric tape with the subjects standing upright; the average value of each measurement was used in the analysis.

2.6. Assessment of adherence to MedDiet

The MedDiet was followed by all participants during the two years of the study. A 17-item energy-reduced MedDiet validated questionnaire (Schröder et al., 2021) was assessed at baseline and after two years to confirm MedDiet adherence at each moment in time and changes during this period. The questionnaire was administered by trained dietitians and consists of 17 questions, each one related to a characteristic item of the MedDiet. If the person surveyed followed the diet correctly in an item, they were given a score of 1 and if they were not, they were given a score of 0. A higher score, with a maximum of 17 points, is considered as a greater MedDiet adherence and a greater quality of the diet.

2.7. Assessment of the physical activity (PA)

The validated Minnesota-REGICOR short PA questionnaire (Elosua et al., 2000; Elosua et al., 1994; Molina et al., 2017) and the validated Spanish version of the Nurses' Health Study questionnaire (Martínez-González et al., 2005) were used to assess PA and sedentary behaviors respectively at baseline and 2-year follow-up.

2.8. GHGs, energy, water, and land use per kg of food

Environmental parameters calculations were done using the Agribalyse® 3.0.1 database created by the French Agency for the Environment an Energy Management (ADEME), in conjunction with the CIQUAL French food composition table (https://agribalyse.ademe.fr/app/aliments, 2013; Colomb et al., 2015). Ecoinvent® is also cooperating with Agribalyse® 3.0.1; data is stored in the Ecoinvent database for non-agricultural procedures (e.g., electricity, transport) and imported production; together they aim to reflect the production and market conditions of European countries. The project was launched in 2009 and the database was published in 2021. The Agribalyse® 3.0.1 database provides reference data on the environmental impacts of agricultural and food products through a database built according to the LCA methodology. It considers each phase in the food chain separated in two steps; production and post-farm procedures. Agricultural production, transport, processing, packaging, distribution and retailing, consumer preparation and disposal of packaging are the steps considered to measure environmental impacts. Wastage at home and transport from retail to the household is not included. The method is based on the international LCA standards: ISO 14040 (ISO 14040:2006(fr), n.d.) and ISO 14044 (ISO 14044:2006(fr), n.d.), LEAP guidelines (https://www.fao.org/partnerships/leap/overview/the-partnership/en/, n.d.) and product environmental footprint (PEF) (European Commission, 2018); the final measurements of each environmental indicator are provided per kg of product. A total of 14 indicators with an environmental footprint single score are available. The Agribalyse® 3.0.1 database methodology can be found extensively explained elsewhere (Kesse-Guyot et al., 2023). Total amounts of GHGs, water use, energy use and land use were used for the present paper and are described below.

GHGs were expressed in kilograms (kg) of carbon dioxide equivalents (CO_2eq). Water use was calculated in cubic meters (m^3) and in correspondence with water consumption and depletion in certain regions, taking scarcity into account. Energy use was calculated in megajoules (MJ) and corresponded to the disposal of non-renewable energy resources like carbon, gas, oil or uranium. Land use largely determines biodiversity. The unit used for the variable land use was estimated using the echo indicator point (Pt), which reflects the impact of an activity on land biodiversity degradation with reference to the "natural state", meaning that higher levels on land degradation would be reflected with higher Pt units (https://agribalyse.ademe.fr/app/aliments, 2013).

All four parameters were estimated at baseline and 2-year follow-up using the following formula:

$$= \frac{g\ of\ each\ reported\ food \times Amount\ of\ the\ Environmental\ Parameter}{1000\ g\ of\ the\ corresponding\ food}$$

The sum of the total impact of the diet was calculated for each parameter separately. The difference between baseline results and two-year results per day was also calculated.

2.9. Statistics

Analyses were performed using SPSS statistical software package version 27.0 (SPPS Inc., Chicago, IL, USA). Data was shown as mean and standard deviation (SD), except for prevalence data, which was expressed as sample size and percentage. Chi-squared test was used for categorical variables and one-way ANOVA and Bonferroni's post-hoc was used for continuous variables. General Linear Model (GLM) was used to relate changes of percentage of UPF consumption and anthropometric characteristics, energy intake, MedDiet adherence, PA and environmental parameters, during the two-year period. GLM was adjusted by sex, age and energy intake, except for the "Energy intake" variable that was only adjusted by sex and age. Bonferroni's post-hoc test was used to show statistically significant differences ($p < 0.05$) between groups within time (a, b, c), between time within groups (*) and between time*group interaction. Linear regressions between percentage of UPF consumption change and GHGs, water use, energy use and land use were conducted. The independent variable was the percentage of UPF consumption change and dependent variables were GHGs, water use, energy use and land use. Fig. 2 shows the linear progression and the regression equation for baseline and 2-year follow-up.

3. Results

Differences on characteristics of sample (sex, educational level, and age) according to changes in UPF consumption in two years are shown in Table 1. T1 (Maximum percentage of UPF reduction) experienced an average reduction of 8.7 %; T2 (Medium percentage of UPF reduction) an average reduction of 2.0 %; and T3 (Minimum percentage of UPF reduction) an average increase of 2.4 %. There were more men in the groups with a maximum (T1) and medium (T2) %UPF reduction in comparison with the minimum reduction group (T3), where there were more women. "Primary School", "Secondary School" and "College School Technician" educational levels were more usual among participants in T1, while more "Bachelor's

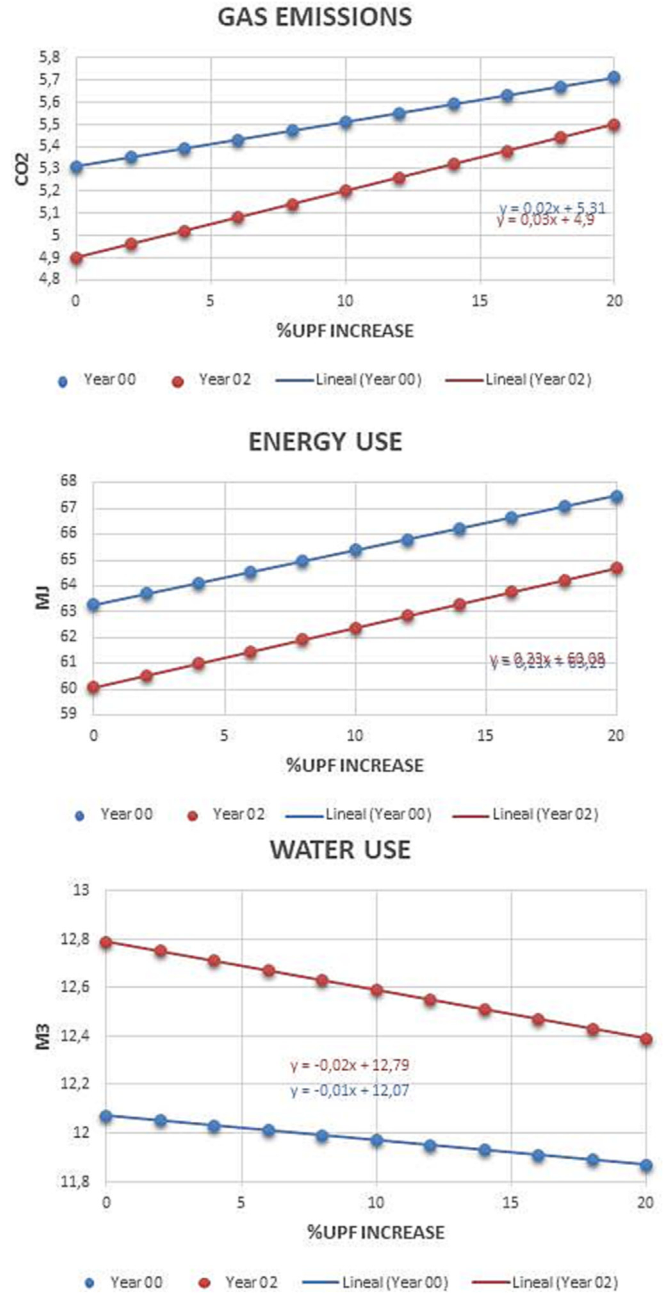

Fig. 2. Linear progression of environmental parameters per years and supposed increase of %UPF consumption.

degree" participants were found in T3. Participants with a major reduction of UPF consumption (T1) were younger.

Table 2 shows the contribution of food groups and NOVA groups, expressed in grams, according to changes in UPF consumption after two-year-follow-up. All food groups' contribution were significative ($p < 0.001$) except for the "eggs" group. T1 showed higher decreases in sweets, red and processed meat, and pre-cooked products, with a significant increase in consumption of fruits and vegetables and a slight increase in white meat, fish, and nuts. T3 showed higher decrease in dairy but lower decrease in red and processed meat and pre-cooked products than T1 and T2, with a decrease in fruits and vegetables and a slight increase in sweets. The four NOVA group categories were also distributed by the mentioned tertiles. T1 showed an average increase of 156.2 g of unprocessed foods and an average decrease of 196.3 g of ultra-processed food while T3 showed an average reduction of 70.8 g of unprocessed foods and an average increase of 48.7 g of ultraprocessed food.

Table 3 shows changes in characteristics of sample through time in weight (kg), BMI (kg/m^2), energy intake (kcal/day), MedDiet adherence, and PA according to the changes in UPF consumption. Weight, BMI and energy intake decreased in all tertiles ($p < 0.001$). There was a decreasing gradient of weight related to tertiles of reduction on UPF consumption, with a mean difference of −2.6 kg, −2.1 kg and, −1.2 kg in T1, T2 and T3, respectively ($p < 0.001$). Likewise, BMI decreased by 0.9 kg/m^2, 0.7 kg/m^2, and 0.4 kg/m^2 ($p < 0.001$), and energy intake was reduced by 347 kcal/day, 181 kcal/day, and 94.5 kcal/day respectively in T1, T2 and T3 ($p < 0.001$). MedDiet adherence enhanced in all tertiles ($p < 0.001$), with an increase of 3.9 points in T1, compared to 3.3 and 2.2 points in T2 and T3, respectively ($p < 0.001$). Time per group (time*group) differences were not found significant for physical activity variables except for moderate PA ($p = 0.002$), showing an increase of metabolic equivalents of task (METs) (295.8 min/week) through two years for people with the highest UPF reduction (T1).

Table 4 shows changes through time for GHGs, water use, energy use and land use. Participants in T1 had significantly ($p < 0.001$) higher reductions of GHGs (−0.6 kg CO2eq compared to −0.3 and −0.3 kg CO2eq in T2 and T3, respectively), and energy consumption (−5.3 MJ compared −2.8 and −3.1 MJ in T2 and T3, respectively) while their water use increased more over time (0.9 m^3) than in other tertiles (0.8 and 0.3 m^3 in T2 and T3, respectively). Land use appeared to not be significative ($p = 0.840$).

Fig. 2 represents linear trends of the three significative environmental parameters if UPF consumption would have been increased at baseline and 2-year follow-up. Higher percentage of UPF consumption would suppose an increase of GHGs and use of energy and a decrease of water use in both years. Lower amounts of water use, and higher energy consumption and CO_2 emitted would be expected at the 2-year follow-up with respect to baseline if the percentage of UPF increases.

4. Discussion

This study shows that a lower UPF consumption may contribute to environmental sustainability in terms of reducing emissions of GHGs and energy use, while the use of water may be increased.

Recent reviews (Lane et al., 2021; Pagliai et al., 2021) warn that a higher consumption of UPFs is a leading cause for suffering non-communicable diseases, overweight, and obesity. It agrees with current results, since a reduction in BMI, weight, and especially energy intake is observed in participants as reduction of UPF consumption was higher. In an inpatient randomized controlled trial, energy intake and weight gain were higher in participants eating the ultra-processed diet compared to patients following unprocessed diet for two weeks (Hall et al., 2019). Increasing consumption of UPF was reported in both developed and developing countries, reducing overall diet quality and having detrimental health impact (Moubarac et al., 2013; Monteiro et al., 2011). UPF was also related to cancer prevalence (Fiolet et al., 2018; Romaguera et al., 2021), visceral fat deposition (Konieczna et al., 2021) and dysregulation of the gut microbiota affecting cognitive health (Martínez Leo and Segura Campos, 2020).

Food groups were considered in this study to show foods in higher-consumption UPF diets. High level of processed meat in participants' diet was found as a driver for UPF environmental impacts (Anastasiou et al., 2022a). Participants with higher reductions in UPF consumption also had higher reductions of red and processed meat in current study. Dairy products were also contributors to the environmental impact (Seves et al., 2017). However, participants with highest UPF reductions in the current study, showed very slight reductions in dairy consumption. This reflects how the NOVA system classifies food groups according to their processing degree, with milk and yogurt classified as "Unprocessed or minimally processed foods", and cheeses were classified as "Processed foods", but none were classified as "Ultra-processed", nor contributing to the environmental footprint from the processing point of view. The current study shows how UPF may be replaced with moderate amounts of white meat or fish. Moreover, consuming cereals, legumes, fruits and vegetables according to energy needs would be beneficial for people health and the environment.

Table 1
Descriptive characteristics of sample according to changes in ultra-processed food consumption.

	T1: Maximum %UPF reduction § (n = 1956)	T2: Medium %UPF reduction § (n = 1956)	T3: Minimum %UPF reduction § (n = 1956)	p
	n (%)	n (%)	n (%)	
Sex				
Men	1078 (55)	1002 (51.1)	959 (49)	0.001
Women	881 (45)	959 (48.9)	1000 (51)	
Educational level				
Primary school	262 (13.4)	231 (11.8)	241 (12.3)	0.030
Secondary school	184 (9.4)	174 (8.9)	167 (8.5)	
College school technician	596 (30.4)	582 (29.7)	525 (26.8)	
Bachelor's degree	917 (46.8)	974 (49.7)	1026 (52.4)	
	Mean (SD)	Mean (SD)	Mean (SD)	p
Baseline Age (years)	64.5 (4.9)	65.2 (4.7)	65.3 (4.9)	<0.001

Abbreviations: SD: Standard deviation. UPF: Ultra-processed food. T1: Tertile 1. T2: Tertile 2. T3: Tertile 3. § Differences in %UPF consumption between baseline and at 2-year follow-up distributed in tertiles T1: Maximum %UPF reduction: ≤ −37,839; T2: Medium %UPF reduction: −3.7838 thru −0.5537; T3: Minimum %UPF reduction: ≥ −0.5536. Average changes in %UPF consumption by group were: -8.7 % (T1), −2.0 % (T2) and +2.4 % (T3). Differences in means between groups were tested by one-way ANOVA and Bonferroni's post hoc (different letters show differences between groups). Differences in prevalence's across groups were examined using χ^2.

Table 2
Food groups and NOVA groups according to changes in ultra-processed food consumption.

		T1: Maximum %UPF reduction § (n = 1956)	T2: Medium %UPF reduction § (n = 1956)	T3: Minimum %UPF reduction § (n = 1956)	Time* group ‡
		mean (SD)	mean (SD)	mean (SD)	
Dairy (g)	Baseline	311.7 (191.2) $^{a\ b}$	334.5 (195.2) $^{a\ c}$	354.2 (212.5) $^{b\ c}$	<0.001
	2 year	307.4 (191.3) ^{b}	311.6 (181.9) ^{c}	300.1 (179.3) $^{b\ c}$	
	▲	−0.4 (191.4) $^{d\ e}$	−22.8 (186.2) * $^{d\ f}$	−54.1 (191.0) * $^{e\ f}$	
Sweets (g)	Baseline	91.8 (71.9) $^{a\ b}$	56.1 (39.0) $^{a\ c}$	48.8 (43.0) $^{b\ c}$	<0.001
	2 year	34.9 (33.6) $^{a\ b}$	31.7 (29.5) $^{a\ c}$	50.9 (48.6) $^{b\ c}$	
	▲	−56.8 (67.6) * $^{d\ e}$	−24.4 (33.4) * $^{d\ f}$	2.1 (44.5) * $^{e\ f}$	
Eggs (g)	Baseline	24.4 (13.2)	23.9 (12.2)	24.3 (11.8)	0.261
	2 year	25.5 (12.3)	25.4 (11.4)	25.5 (13.8)	
	▲	1.1 (15.5) *	1.5 (13.3) *	1.2 (15.0) *	
White meat (g)	Baseline	60.3 (34.3) $^{a\ b}$	62.3 (33.4) ^{a}	64.5 (35.4) ^{b}	<0.001
	2 year	66.2 (30.6)	68.4 (31.1) ^{c}	65.4 (31.3) ^{c}	
	▲	5.8 (37.3) * ^{e}	6.1 (35.8) * ^{f}	0.9 (38.4) $^{e\ f}$	
Red and processed meat (g)	Baseline	97.7 (54.3) $^{a\ b}$	84.8 (43.9) $^{a\ c}$	80.6 (43.6) $^{b\ c}$	<0.001
	2 year	61.4 (36.7) ^{b}	60.9 (36.4) ^{c}	69.3 (40.0) $^{b\ c}$	
	▲	−36.3 (53.8) * $^{d\ e}$	−23.9 (44.3) * $^{d\ f}$	−11.2 (44.4) * $^{e\ f}$	
Fish and seafood (g)	Baseline	100.2 (47.4) $^{a\ b}$	103.8 (47.3) ^{a}	105.9 (48.9) ^{b}	<0.001
	2 year	110.3 (46.6) ^{b}	110.4 (44.1) ^{c}	106.0 (46.9) $^{b\ c}$	
	▲	10.0 (54.0) * $^{d\ e}$	6.6 (50.3) * $^{d\ f}$	0.15 (53.0) $^{e\ f}$	
Fruits and vegetables (g)	Baseline	651.8 (264.9) $^{a\ b}$	727.0 (264.7) $^{a\ c}$	759.5 (311.2) $^{b\ c}$	<0.001
	2 year	781.0 (266.0) ^{b}	808.2 (267.2) ^{c}	752.5 (253.6) $^{b\ c}$	
	▲	129.2 (312.9) * $^{d\ e}$	81.1 (311.6) * $^{d\ f}$	−7.0 (332.4) * $^{e\ f}$	
Cereals and legumes (g)	Baseline	241.5 (100.9) $^{a\ b}$	247.6 (100.9) ^{a}	243.1 (101.7) ^{b}	<0.001
	2 year	215.7 (82.8) ^{b}	216.3 (80.4) ^{c}	214.6 (83.7) $^{b\ c}$	
	▲	−25.7 (111.2) * $^{d\ e}$	−31.3 (107.9) * $^{d\ f}$	−28.5 (111.44) * $^{e\ f}$	
Nuts (g)	Baseline	17.1 (19.5) $^{a\ b}$	18.4 (21.0) ^{a}	19.2 (22.4) ^{b}	<0.001
	2 year	30.6 (21.9) ^{b}	31.0 (21.3) ^{c}	28.5 (21.8) $^{b\ c}$	
	▲	13.5 (25.9) * $^{d\ e}$	12.5 (25.5) * $^{d\ f}$	9.3 (26.7) * $^{e\ f}$	
Pre-cooked products (g)	Baseline	11.4 (17.3) $^{a\ b}$	7.0 (9.9) ^{a}	6.4 (10.3) ^{b}	<0.001
	2 year	5.1 (9.2) $^{a\ b}$	4.4 (7.9) $^{a\ c}$	6.1 (9.9) $^{b\ c}$	
	▲	−6.2 (16.1) * $^{d\ e}$	−2.6 (9.8) * $^{d\ f}$	−0.2 (11.2) * $^{e\ f}$	
Un-processed (g)	Baseline	1339.4 (394.8) $^{a\ b}$	1452.1 (397.2) $^{a\ c}$	1514.2 (444.2) $^{b\ c}$	<0.001
	2 year	1495.6 (388.8) ^{b}	1520.8 (367.2) ^{c}	14,443.3 (366.2) $^{b\ c}$	
	▲	156.2 (430.1) * $^{d\ e}$	68.7 (411.5) * $^{d\ f}$	−70.8 (436.7) * $^{e\ f}$	
Mini-processed (g)	Baseline	53.4 (23.2) $^{a\ b}$	52.9 (21.6) ^{a}	52.1 (22.2) ^{b}	0.008
	2 year	51.0 (18.6)	52.0 (17.9) ^{c}	51.7 (18.7) ^{c}	
	▲	−2.3 (24.1) ^{e}	−0.8 (22.9) *	−0.4 (22.9) * ^{e}	
Processed (g)	Baseline	421.4 (276.0) $^{a\ b}$	428.8 (289.1) $^{a\ c}$	446.2 (326.5) $^{b\ c}$	<0.001
	2 year	342.6 (237.1) ^{a}	355.3 (238.6) ^{a}	361.4 (246.3)	
	▲	−78.7 (243.0) * $^{d\ e}$	−73.4 (239.2) * $^{d\ f}$	−84.8 (267.9) * $^{e\ f}$	
Ultra-processed (g)	Baseline	287.0 (209.2) $^{a\ b}$	114.5 (80.4) $^{a\ c}$	103.3 (99.1) $^{b\ c}$	<0.001
	2 year	90.7 (99.6) $^{a\ b}$	71.6 (70.4) $^{a\ c}$	152.0 (156.0) $^{b\ c}$	
	▲	−196.3 (165.3) * $^{d\ e}$	−42.8 (34.3) * $^{d\ f}$	48.7 (101.2) * $^{e\ f}$	

Abbreviations: SD: Standard deviation. UPF: Ultra-processed food. T1: Tertile 1. T2: Tertile 2. T3: Tertile 3. § Differences in %UPF consumption between baseline and at 2-year follow-up distributed in tertiles: T1: Maximum %UPF reduction: ≤ −37,839; T2: Medium %UPF reduction: −3.7838 thru −0.5537; T3: Minimum %UPF reduction: ≥ −0.5536. Average changes in %UPF consumption by group were: -8.7 % (T1), −2.0 % (T2) and +2.4 % (T3). General Lineal Model was calculated between baseline and year 2 follow-up adjusted by age, sex and energy intake. Different letters show significant differences ($p < 0.05$) between groups within time (a, b, c), between time within groups (*) and between time*group interaction (d, e, f) by the Bonferroni post-hoc test ($p < 0.05$).

Table 3
Changes in characteristics of sample according to the level of reduction in UPF consumption.

		T1: Maximum %UPF reduction § (n = 1956)	T2: Medium %UPF reduction § (n = 1956)	T3: Minimum %UPF reduction § (n = 1956)	Time* group ‡
		mean (SD)	mean (SD)	mean (SD)	
Weight	Baseline	87.1 (13)	85.8 (12.7)	85.6 (13)	<0.001
	2 year	84.4 (13.3) ^{b}	83.7 (12.9)	84.3 (13.4) ^{b}	
	▲	−2.6 (4.7) * $^{d\ e}$	−2.1 (4.5) * $^{d\ f}$	−1.2 (4.4) * $^{e\ f}$	
BMI (kg/m^2)	Baseline	32.5 (3.4)	32.4 (3.4)	32.3 (3.4)	<0.001
	2 year	31.6 (3.7) ^{b}	31.6 (3.6)	31.9 8 (3.7) ^{b}	
	▲	−0.9 (1.7) * $^{d\ e}$	−0.7 (1.7) * $^{d\ f}$	−0.4 (1.6) * $^{e\ f}$	
Med-Diet ADH	Baseline	7.8 (2.5) $^{a\ b}$	8.7 (2.6) $^{a\ c}$	8.9 (2.7) $^{b\ c}$	<0.001
	2 year	11.8 (2.8) ^{b}	12 (2.6) ^{c}	11.1 82.7) $^{b\ c}$	
	▲	3.9 (3.2) * $^{d\ e}$	3.3 (3.1) * $^{d\ f}$	2.2 (3.1) * $^{e\ f}$	
Energy (kcal/day)	Baseline	2529.1 (679) $^{a\ b}$	2372.6 (570.2) ^{a}	2351 (591.6) ^{b}	<0.001
	2 year	2182 (505.5) ^{b}	2191.6 (461.3) ^{c}	2256.5 (509.3) $^{b\ c}$	
	▲	−347 (664.8) * $^{d\ e}$	−181 (535.5) * $^{d\ f}$	−94.5 (570.2) * $^{e\ f}$	
Light PA (METs)┼	Baseline	809.5 (982.4) ^{b}	782.1 (979.9)	735.9 (918) ^{b}	0.406
	2 year	899 (1054.7)	898.1 (1001.9)	881.4 (960.6)	
	▲	89.5 (1229) *	115.9 (1171.4) *	145.2 (1142.1) *	
Moderate PA (METs)┼	Baseline	850.9 (1355.8) $^{a\ b}$	1018.6 (1563.1) ^{a}	1053.4 (1683.4) ^{b}	0.007
	2 year	1146.8 (1591.5)	1207.9 (1690.6)	1144.6 (1852.7)	
	▲	295.8 (1607.1) * ^{e}	189.3 (1746.2) *	91.7 (1729.5) * ^{e}	
Intense PA (METs)┼	Baseline	720 (1375.7)	786.7 (1447.7)	816.5 (1485)	0.862
	2 year	952.7 (1615.3)	1001.3 (1626.2)	1004.2 (1784.7)	
	▲	232.6 (1656.5) *	214.6 (1635.7) *	187.8 (1773.5) *	
Total PA (METs)┼	Baseline	2380.5 (2174.9) $^{a\ b}$	2587.5 (2319.1) ^{a}	2605.9 (2469.3) ^{b}	0.189
	2 year	2998.6 (2420.3)	3107.4 (2504.3)	3030.2 (2684.9)	
	▲	618.1 (2515.6) *	519.9 (2464.5) *	424.8 (2692.9) *	

Abbreviations: BMI: Body Mass Index. Med-Diet ADH: Mediterranean Diet Adherence. PA: Physical Activity. SD: Standard deviation. UPF: Ultra-processed food. T1: Tertile 1. T2: Tertile 2. T3: Tertile 3. ┼ Measured in METs (Metabolic equivalents of task) min/week. § Differences in %UPF consumption between baseline and at 2-year follow-up distributed in tertiles: T1: Maximum %UPF reduction: ≤ −37,839; T2: Medium %UPF reduction: −3.7838 thru −0.5537; T3: Minimum %UPF reduction: ≥ −0.5536. Average changes in %UPF consumption by group were: -8.7 % (T1), −2.0 % (T2) and +2.4 % (T3). General Lineal Model was calculated between baseline and year 2 follow-up adjusted by age, sex and energy intake. Variable: "Energy (kcal/day)" was only adjusted by age, and sex. Different letters show significant differences ($p < 0.05$) between groups within time (a, b, c), between time within groups (*) and between time*group interaction (d, e, f) by the Bonferroni post-hoc test ($p < 0.05$).

Higher adherence to the MedDiet was found in the current study to be a strategy for reducing UPF consumption (García et al., 2023). This is explained by the defining fact that MedDiet, beyond nutritional content considerations commented elsewhere (Fardet and Rock, 2020a), is made up of mainly fresh products, with a low level of processing. A linear association of MedDiet with a sustainability score had already been described considering the same four environmental parameters in the current study (Grosso et al., 2020), demonstrating that a higher MedDiet adherence was specifically related with lower GHGs (García et al., 2023; Grosso et al., 2020).

A previous study on GHGs, and use of water, land, and energy found similar results, being notable in terms of water use (Fresán et al., 2020). Less ultra-processed diets like MedDiet, which is based on plant-based food groups, were also associated with greater amount of water use. This may be due to the fact that growing vegetables, fresh fruits and nuts need higher amount of water, although it is not as applicable to cereals and legumes, as these are mostly dryland crops (Fresán et al., 2020). This is consistent with the results of a recent study conducted in the Netherlands which found that higher UPF consumption was associated with higher

Table 4
Changes in environmental impacts according to the level of reduction in UPF consumption.

		T1: Maximum %UPF reduction § (n = 1956)	T2: Medium %UPF reduction § (n = 1956)	T3: Minimum %UPF reduction § (n = 1956)	Time* group ‡
		mean (SD)	mean (SD)	mean (SD)	
GHGs	Baseline	5.5 (1.5) ^{b}	5.3 (1.4)	5.4 (1.4) ^{b}	
(Kg CO_2eq)	2 year	4.9 (1.2)	5 (1.2)	5.1 (1.2)	0.006
	▲	−0.6 (1.5) * ^{e}	−0.3 (1.3) *	−0.3 (1.3) * ^{e}	
Water Use	Baseline	11.7 (3.9) $^{a\ b}$	11.9 (3.9) $^{a\ c}$	12.1 (4.2) $^{b\ c}$	<0.001
(m^3)	2 year	12.6 (3.9) ^{b}	12.8 (3.7) ^{c}	12.5 (3.6) $^{b\ c}$	
	▲	0.9 (4.7) * $^{d\ e}$	0.8 (4.6) * $^{d\ f}$	0.3 (4.7) $^{e\ f}$	
Energy Use	Baseline	66.1 (17.1) $^{a\ b}$	63.9 (15.6) $^{a\ c}$	65 (16.2) $^{b\ c}$	<0.001
(MJ)	2 year	60.8 (14.4)	61.1 (13.3)	61.8 (14.3)	
	▲	−5.3 (17.2) * ^{e}	−2.8 (15) * ^{f}	−3.1 (15.7) * $^{e\ f}$	
Land Use	Baseline	281.0 (88.9) ^{b}	271.9 (82.3)	271.8 (82.2) ^{b}	0.840
(Pt)	2 year	239.8 (72.5)	243.4 (72.1)	249.6 (73.9)	
	▲	−41.1 (87.4) *	−28.5 (77.5) *	−22.1 (80.8) *	

Abbreviations: SD: Standard deviation. GHGs: Greenhouse gas emissions. Kg CO_2eq: Kilograms of Carbon Dioxide equivalents. m^3: Cubic meters; MJ: Megajoules. Pt: points of land use. UPF: Ultra-processed food. T1: Tertile 1. T2: Tertile 2. T3: Tertile 3§ Differences in %UPF consumption between baseline and at 2-year follow-up distributed in tertiles: T1: Maximum %UPF reduction: ≤ −37,839; T2: Medium %UPF reduction: −3.7838 thru −0.5537; T3: Minimum %UPF reduction: ≥ −0.5536. Average changes in %UPF consumption by group were: −8.7 % (T1), −2.0 % (T2) and +2.4 % (T3). General Lineal Model was calculated between baseline and after 2-year follow-up adjusted by age, sex and energy intake. Different letters show significant differences ($p < 0.05$) between groups within time (a, b, c), between time within groups (*) and between time*group interaction (d, e, f) by the Bonferroni post-hoc test ($p < 0.05$).

GHGs and lower water use, and thus the replacement of UPF by unprocessed and minimally processed foods may suppose increases in water use (Vellinga et al., 2022). A Brazilian study found initial linear associations between UPF and water footprints. After adjusting by total energy intake, associations vanished, indicating that dietary contributions of UPF increase the use of water because of the indirect increment on energy intake (Garzillo et al., 2022). Current results were also adjusted by energy intake and are aligned with the results of both studies in the Netherlands and Brazil. Another previous paper found how the negative association regarding to water use was strengthened when adjustments by energy intake were conducted (Kesse-Guyot et al., 2023). Energy intake should be considered when talking about UPF sustainability. It is one of the main drivers of negative environmental impact, and a primary characteristic of UPF-rich diets; a 15 % of overweight/obesity could be attributed to consumption of >17 % of energy intake from UPF (Canhada et al., 2020).

Land use was not significative in the current study. Land-use impacts from UPF are mainly driven by processed meat products; relatively low contributions were found to land use for meat-free UPF products when compared to processed meat products (Anastasiou et al., 2022a). The contribution of red and processed meat and pre-cooked foods is low in the current participants' diets, since they tend to follow the MedDiet. Even if a notable higher decrease can be seen in the group which reduced UPF the most, all three groups showed reductions on those food groups, which explain the lack of association between UPF and land use.

There is still considerable inter-study variability in the environmental impact results regarding to UPF, which depends on the food classification used, the production steps accounted for, whether processed meat is included, and whether proper energy intake adjustments are made. The results for GHGs and energy use seem to be more consistent, indicating how UPF is one of the major contributors to these parameters when compared to other food groups (Anastasiou et al., 2022a; Anastasiou et al., 2022b).

In a study on UPF environmental impact in Brazil from 1987 to 2018, diet-related GHGs increased by 21 %, diet-related water footprint increased by 22 % and diet-related ecological footprint increased by 17 %; products from the fourth NOVA group (UPF and drinks) were primarily responsible for these changes (da Silva et al., 2021). The Food and Agriculture Organization (FAO) indicated that UPF consumption in Australia represent a third of the diet-related environmental effects corresponding to a 35 % of water use, 39 % of energy use, 33 % of CO_2eq and 35 % of land use, which could double in GHGs per capita by 2050 if dietary trends continue as projected (Machado et al., 2019; Monteiro et al., 2019b). Even though the highest emission of GHGs was still due to animal products (meat and dairy) (Seves et al., 2017; Fresán et al., 2020; Clonan et al., 2015; Notarnicola et al., 2017) in comparison with plant and low-calorie processed products, UPF were associated with intensive agriculture and livestock practices that threaten the sustainability of the food system (Fardet and Rock, 2020b).

In a recent study on Spanish adult population attitudes about a sustainable diet, participants attributed the main negative environmental impact to processed foods and beverages, and men appeared to have a better understanding in relation to the term sustainability (García-González et al., 2020). A very recent review of different policies on reducing UPF consumption concluded that policies such as taxation, marketing or subsidies would be beneficial for the climate-environment-related sustainability as well as health (Popkin et al., 2021).

In a healthy and sustainable diet, it is highly recommended to include the recommendations of UNESCO and the Sustainable Development Goals from the United Nations System (United Nations (UN), n.d.), which advocate for recovering the traditional diet patterns of each region appropriate to the climate, natural resources, and cultural heritage, with some modifications when necessary to complement them nutritionally. In this way, the recent update of the MedDiet pyramid (Serra-Majem et al., 2020) is also aligned with the guidelines of the global food model proposed by the EAT Lancet study for 2050 (Willett et al., 2019). A holistic process to include sustainability, and specifically UPF environmental impacts, needs to be adequately integrated into FDGD so that society has appropriate guidelines on how to identify and consume these kind of products (Mazac et al., 2021).

5. Strengths and limitations

The longitudinal design allowing for causality evaluation is the first strength of this study, followed by the great sample used. The use of the NOVA system for food classification permits comparison with other studies that considered this same system. Environmental parameters calculations for each participant diet were based in a French actualized database that considered each step of the LCA; agricultural production, transport, processing, packaging, distributions and retailing, consumer and disposal of packaging are the steps considered to measure environmental impacts. The use of four environmental parameters like GHGs, water use, energy use, and land use represents one of the greatest strengths of the paper, which permits a holistic evaluation of environmental impact.

The first limitation for this study is the lack of a validated questionnaire that measures UPF consumption. The use of the FFQ provides an overview, but it is not precisely assessing UPF consumption. For example, fruit juices, milkshakes, meatballs, hamburgers and pizza can be consumed as artisanal, but here they were also considered industrial and classified as ultra-processed products. FFQ does not distinguish between plain, sweetened, or flavored varieties of yogurts and whole-grain cereals so these foods were considered to belong to unprocessed or minimally processed foods group. The use of the unit “Pt” for land calculations may be a limitation, since it is a specific calculation that cannot be compared to other articles that do not use the Agribalyse® 3.0.1 database. Spain does not currently have its own database for food environmental impacts. Using a French database instead of a Spanish one can be a limitation since there can be differences in the food supply between countries which may result in slight changes to the environmental values. However, we determined that Agribalyse® 3.0.1 was an appropriate option since the European Union has a market regulated by the Treaty on the Functioning of the European Union (TFEU) with the objective to establish a common internal market. Additionally, the EU food market is specifically regulated as well. Regulation (EC) No. 178/2002 of the European Parliament and of the Council of January 28, 2002, declares that food circulation between member states of the European Union should be based on common concepts, principles, and procedures; free movement of food and feed within the EU is only allowed if the food and feed safety requirements do not differ significantly from one Member State to another. Finally, the study population age is in between 55–75 for men and 60–75 for women which is an impediment for extrapolating our data to a younger population.

6. Conclusions

The current study demonstrated that low consumption of ultra-processed foods may contribute to environmental sustainability. The processing threshold of the food consumed should be considered not only for nutritional advice on health but also for environmental protection.

Ethics approval and consent to participate

Informed written consent was provided by all participants and the study protocol and procedures were approved by ethical committees according to the ethical standards of the Declaration of Helsinki by all the 23 participating institutions.

Consent for publication

Informed consent was obtained from all subjects involved in the study. The results and writing of this manuscript followed the Committee on Publication Ethics (COPE) guidelines on how to deal with potential acts of misconduct, maintaining the integrity of the research and its presentation following the rules of good scientific practice, the trust in the journal, the professionalism of scientific authorship, and the entire scientific endeavour. Written informed consent has been obtained from the patient(s) to publish this paper.

CRediT authorship contribution statement

All the PREDIMED-Plus investigators (SG, RP, MM-M, LA, MR, MAM-G, JS-S, DC, AG, JV, DR, JL-M, RE, FJT, JL, LS-M, BR-G, XP, JJG, PM, JV, CV, LD, ER, CS-O, PG-S, CV-H, RC, IA, LG-G, EG-G, SC-B, CT-M, AC, JMS-L, JCC, RB, NK, OC, MAZ, JV-L, MB-R, SH-D, RC, JAT, VM-S, CB) contributed to study concept and design and to data extraction from the participants. SG, and CB performed the statistical analyses. SG, CB, and JAT drafted the manuscript. All authors reviewed the manuscript for important intellectual content and approved the final version to be published.

Data availability

Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval of the PREDIMED-Plus Steering Committee. There are restrictions on the availability of data for the PREDIMED-Plus trial, due to the signed consent agreements around data sharing, which only allow access to external researchers for studies following the project purposes. Requestors wishing to access the PREDIMED-Plus trial data used in this study can make a request to the PREDIMED-Plus trial Steering Committee chair: jordi.salas@urv.cat. The request will then be passed to members of the PREDIMED-Plus Steering Committee for deliberation.

Declaration of competing interest

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