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Quantifying the environmental human health burden of food demand in Spain: A life cycle assessment study

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ABSTRACT

The negative impacts of current dietary patterns in Spain on both human health and the environment are well documented. While the strong connection between environmental degradation and human health is widely recognized, no studies have evaluated how environmental disruption generated specifically by Spain's food systems translates into health outcomes. To address this gap, this study quantifies the human health burden linked to the environmental impacts of Spain's food demand, assessing the potential benefits of changing consumer behavior. A life cycle assessment study of the environmental human health impacts of food consumption and waste in Spain during 2022 was performed, applying the IMPACT World + v2.1 Life Cycle Impact Assessment method, and ReCiPe 2016 v1.1 as sensitivity analysis. Scenarios involving the partial or full replacement of red and processed meat with white meat, meat and dairy with plant-based options, and the mitigation of consumers' food waste were analyzed in terms of environmental human health and nutritional outcomes. The findings showed that meat and fish were the food groups with higher environmental human health impact, both on a weight and protein content basis. Meat, fish, and dairy contributed 55 % of dietary environmental human health damage, with total food demand resulting in 447,152 disability-adjusted life years. Replacing meat and dairy with plant-based options could reduce this burden by up to 30 % in a scenario of full substitution. Eliminating consumers' food waste could further lower it by an additional 5 %. Nutritional analyses showed that these dietary changes would result in diets more closely aligned with World Health Organization nutritional guidelines. Transitioning towards more plant-based diets and reducing food waste can significantly decrease environmental human health damage while fostering healthier, more nutritious, and more sustainable dietary practices in Spain. Policymakers should consider these strategies in public health initiatives to mitigate planet and human health crises.

1. Introduction

Human health is influenced by a wide range of factors. On the one hand, intrinsic aspects such as genetics, race, sex, and age can determine an individual's predisposition to certain diseases (Budreviciute et al., 2020). While these factors are non-modifiable, lifestyle choices can modulate their effects. Habits such as alcohol and tobacco use, physical inactivity, diet, and stress management play a crucial role in shaping overall health outcomes (Budreviciute et al., 2020; IHME, 2021). In addition to these intrinsic and behavioral factors, which have traditionally received great attention, external environmental conditions also have a significant impact on human health. Current scientific evidence supports that reducing the environmental impacts of human activities should be a top public health priority. Since 2016, The Lancet Countdown has been highlighting the health impacts of climate change, including respiratory problems, heat-related illnesses, and vector-borne diseases. (Lancet Countdown) Additionally, the human health burden associated with other air pollutants, such as ozone-depleting substances, particulate matter, and ionizing radiation, can also be substantial. Those environmental disruptions result in various health issues, ranging from short-term respiratory problems to long-term effects like cancer. Taken together, it is estimated that 23 % of global deaths are attributable to modifiable environmental risk factors (Prüss-Üstün et al., 2016).

Among human activities, dietary choices play a crucial role in

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shaping human health, influencing it both directly—through food consumption—and indirectly, by contributing to environmental pollution. On one hand, suboptimal diets are associated with an increased risk of non-communicable diseases, including cardiovascular diseases, diabetes, obesity, and certain types of cancer (IHME, 2021). On a global scale, unhealthy dietary patterns are responsible for approximately 11 million deaths and 255 million disability-adjusted life years (DALY) annually (Willett et al., 2019; Afshin et al., 2019). On the other hand, the food system is also a major contributor to environmental pollution (e.g., accounting for 34 % of global greenhouse gas emissions (GHGe) (Crippa et al., 2021), and 78 % of eutrophication (Poore and Nemecek, 2018)), resource overuse (e.g., 37 % of land use, (Food and Agriculture Organization of the United Nations) and 69 % of freshwater withdrawals (Food and Agriculture Organization of the United Nations)) and is the main driver of biodiversity loss (Benton et al., 2021). Certainly, the current food system exceeds several planetary boundaries (Willett et al., 2019; Campbell et al., 2017; Rockström et al., 2020). Although the evidence linking the food system's environmental disruption to human health impacts is still emerging, current findings support the notion that changes to the food system—particularly in dietary patterns—can yield substantial direct and indirect benefits for human health (Springmann et al., 2023; Balasubramanian et al., 2021; Crippa et al., 2022; Walker et al., 2019; Domingo et al., 2021; Liu et al., 2021; Stylianou et al., 2021).

In Spain, the trajectory of research regarding the impact of dietary choices aligns well with global trends, focusing primarily on dietary healthiness and environmental impacts. It is known that the transition from the traditional plant-based Mediterranean diet to a Western diet has significantly contributed to the rise of chronic diseases, including obesity, cardiovascular diseases, and diabetes (Martínez-González and Martín-Calvo, 2013). National statistics reveal that more than half of the adult population in Spain is overweight, and the prevalence of diet-related conditions continues to escalate. (Ministerio de Sanidad) In fact, Spaniards lose 743,070 DALYs annually due to unhealthy dietary patterns (IHME, 2021). On the other hand, the food system has become the leading contributor to environmental degradation also in Spain (Ministerio de Consumo/EC-JRC, 2022). Food consumption is the leading behavioral driver for many environmental problems, including GHG emissions (46 %), land use (77 %), water consumption (73 %), ozone depletion (80 %), particulate matter emissions (61 %), and the release of toxic substances (accounting for 43 % of carcinogenic and 65 % of non-carcinogenic substances) (Ministerio de Consumo/EC-JRC, 2022). Additionally, it should not be overlooked that Spaniards waste 1.2 billion kilograms of food every year (Ministerio de Agricultura, 2022), further contributing to unnecessary environmental impacts. Nevertheless, the indirect effects on human health from environmental pollution have received no attention so far.

To shed light on their relevance for public health concerns, this study aimed to: 1) assess the environmental human health effects of food products commonly consumed in Spain; 2) quantify the environmental human health impacts associated with food demand in Spain, considering both food consumption and consumers' food waste; 3) analyze the contribution of each food group within the diet to these environmental human health outcomes; and 4) evaluate the potential environmental human health and nutritional consequences of behavioral change in food consumption and waste.

2. Methods

The Life Cycle Assessment (LCA) methodology was employed to assess the human health burden resulting from environmental pollution. LCA is a methodology that quantifies the environmental impacts throughout the course of the entire life cycle of a product, material, organization, or any human activity. The ISO 14040/44:2006 standard (ISO, 2006a; ISO, 2006b), which guides LCA performance, establishes four main stages in an LCA: i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation of the results.

2.1. Goal and scope

The primary goal of this study was to evaluate the human health impacts stemming from the environmental footprint associated with diverse foods, and to estimate the overall environmental human health damage linked to total food demand—encompassing both food consumption and consumer food waste—by residents of Spain in 2022. Additionally, the study aimed to identify the food groups that contribute most significantly to consumption impacts, and to assess the potential environmental human health and nutritional consequences of changing consumption patterns, as well as minimizing consumers' food waste.

The object of assessment was the total demand for food in Spain in 2022, which includes all food consumed and wasted by the Spanish population throughout 2022, covering both household and out-of-home consumption and waste. The functional unit for assessing the environmental human health impacts of specific food items was mass-based (1 kg of ready-to-eat food items). Due to the necessity of a protein transition to achieve a food system within planetary boundaries, we also compared protein-rich food categories (i.e., eggs, meat, fish and legumes) using protein content as a functional unit (100g of protein). In this analysis, lard was excluded from the meat category because it is not a protein source.

The system boundaries represent a cradle-to-fork approach, spanning from food production to consumption (Fig. 1). The boundaries encompassed the following phases: agricultural production (including pre- and on-farm processes such as the production of fertilizer or feed ingredients), processing, transport (except for the transport from retail to consumer), packaging (including packaging transport to the industry), distribution, retail, consumer use, and end-of-life, including packaging and food loss and waste disposal within the boundaries.

2.2. Life cycle inventory

The food demand data for this study were obtained from the 2022 annual surveys conducted by the Spanish Ministry of Agriculture, Fisheries, and Food. These surveys captured information on both food demand and consumers' food waste among Spanish residents, covering both household and out-of-home settings (original datasets are available online (Ministerio de Agricultura; Ministerio de Agricultura)).

Food consumption was calculated by subtracting total food waste from total food demand. While the demand data were detailed for each individual food item, the waste data were provided in broader categories. We assumed that these broader categories were composed of the individual items listed in the demand surveys, with waste occurring in proportion to each item's demand. The "ethnic dishes" category related to food waste was excluded from the analysis due to insufficient data to identify individual food items. Then, individual food items were grouped into 16 broad categories. This approach provided a comprehensive understanding of food consumption patterns across various food categories within Spain. Supplementary Tables 1 and 2 detail data related to food consumption and consumers' food waste, respectively.

The surveys identified a total of 397 unique food products. These food products were matched with 637 unique LCIs from the Agribalyse v3.1.1. LCI database (see (Agribalyse) for details on this database). This database was selected for its extensive coverage of hundreds of food items, including processed and ready-to-eat products, which were essential for assessing the large variety of foods identified. Supplementary Tables 1 and 2 detail the attribution of specific LCI items to each food product, along with the adaptations and assumptions made.

Some food products were reported as unspecified items in the demand surveys (e.g., "other types of rice"). In those cases, it was assumed that they encompassed a range of products available in Spain that were not individually identified in the surveys (for instance, "other types of

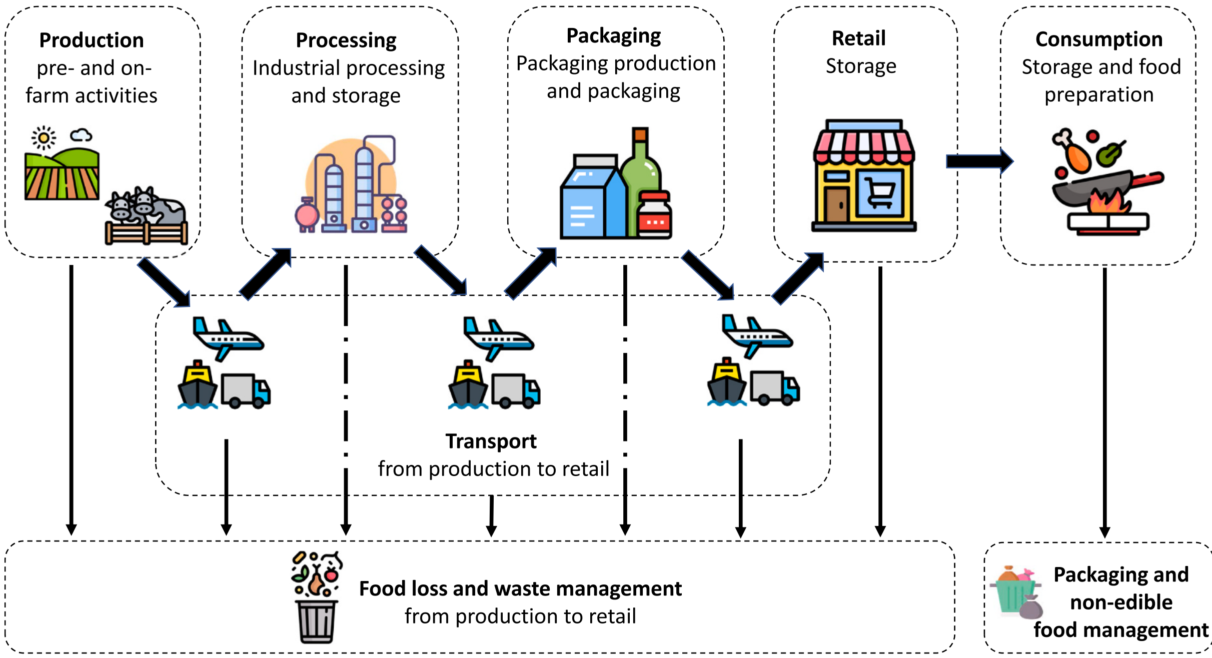

Fig. 1. Life cycle boundaries of the study.

rice" was assumed to include red rice and wild rice). When Agribalyse does not provide specific LCIs for other commonly consumed foods in Spain, the study applied the average LCI of the individual foods reported in the survey within the same category. For instance, "other red meats" was modeled using an average of the LCIs for veal, beef, pork, and lamb.

Economic allocation is predominantly used in Agribalyse, with exceptions like biophysical allocation for dairy husbandry and mass allocation for cheese production. For meat products where economic allocation was relevant to the assessment, three representative cuts were equally considered due to the lack of granular data in the surveys (for instance, for lamb, cuts such as leg, rib chop, and shoulder were included).

The food demand data (and thus, derived food consumption data) collected for this study referred to raw foods (except for ready-to-eat products and out-of-home foods), including both edible and non-edible parts. To contemplate household preparation, we considered the most common cooking methods in Spain and assigned equal weights to each method in the analysis (for instance, the cooking methods for potatoes included boiling, pan-frying, deep-frying, and baking). Conversion factors from the Agribalyse database were applied to convert reported raw food weights into their ready-to-eat edible equivalents, as detailed in Supplementary Tables 1 and 2 In the case of consumers' waste surveys, it was detailed whether the wasted food was raw or cooked. As Agribalyse does not include LCIs for some raw products, we used LCI data for their cooked equivalents and modified them accordingly. For instance, Agribalyse provides data on cooked pizza, but not for raw pizza. Thus, we created a new process for raw pizza using data from cooked pizza adapting energy consumption and the raw-to-cooked weight ratio to represent the raw product. A total of 72 unique LCIs for raw products were developed.

2.2.1. *Alternative scenarios*

One of the objectives of this study was to assess the potential environmental human health and nutritional effects of changing consumer behavior. Specifically, we focused on i) replacing red and processed meat with white meat (Scenario 1); ii) substituting meat and dairy products with plant-based options (Scenario 2); and iii) reducing consumers' food waste (Scenario 3). These measures were selected because: i) swapping red and processed meat for white meat has been proposed as a measure for more environmentally sustainable diets (Clark et al., 2019); ii) diverse organizations such as the Lancet Countdown and the Intergovernmental Panel on Climate Change, have emphasized the need to transition toward more plant-based diets –with a particular focus on reducing meat and dairy consumption– as a pivotal measure in mitigating climate change (Romanello et al., 2022; IPCC, 2019; UK Health Alliance for Climate Change, 2024); iii) reducing consumers' food waste (along with preventing food loss and waste at other phases of the food system) has been pointed out as essential to achieve a food system that operates within planetary boundaries (Springmann et al., 2018).

Those three scenarios were developed with varying intensities, implementing each either partially (50 % change) or fully (100 % change). Additionally, we assessed a combined scenario that includes both the replacement of meat and dairy with plant-based options and a reduction in food waste (Scenario 4). This combined scenario was also evaluated at two levels of intensity: 50 % and 100 % implementation. All dietary replacements were made on an isoquantitative basis. This approach was chosen over isocaloric or isoproteic replacements due to the excessive intake of both energy and protein in the Spanish population (Ruiz et al., 2016). Therefore, ensuring an identical intake of both energy and protein is not essential. Isoserving replacement was also deemed inappropriate, as standard serving sizes can vary significantly between replaced food groups and their substitutes. For instance, while the typical serving size of processed meat is 50 g, that of pulses is 150–200 g. In contrast, isoquantitative replacement allows for more realistic dietary swaps, such as replacing cold cuts with less than one full serving of pulses.

Meat and dairy products were primarily present in their own food categories, but were also used as ingredients in other categories, such as ready-to-eat meals, cakes, and chocolate products. In Scenario 1, within the meat category, red and processed meats were replaced with white meats maintaining the baseline proportional distribution of individual white meat items (e.g., chicken, turkey, offal, etc.), as detailed in Supplementary Table 1. New processes were developed for other food items containing red or processed meat as ingredients in different categories, adapting the original recipes by replacing these meats with chicken (see Supplementary Table 3). In scenario 2, where all meat and dairy were replaced with plant-based alternatives, the meat category was substituted with legumes, which are recommended as the primary plant-based protein source (Agencia Española de Seguridad Alimentaria y Nutricion, 2022). Similarly, it was assumed that legumes would be consumed in the same types and preparation methods (e.g., home-cooked or canned) as in the baseline scenario (see Supplementary Table 1). For dairy products, plant-based alternatives were selected to closely resemble the original dairy items; for instance, milk was replaced with calcium-fortified soy beverages (Supplementary Table 3). Meat-based ready-to-eat meals were replaced with plant-based equivalents, while cakes and chocolate products were replaced with versions excluding milk and butter (e.g., milk chocolate was substituted with dark chocolate). When choosing substitutes for this last category, we prioritized fully plant-based options. However, some replacements may still contain eggs, as Agribalyse lacks fully plant-based options (e.g., cakes). New processes for their fully plant-based versions were not developed because excluding eggs from recipes would modify the industrial processing requirements, and no data is available. Supplementary Table 3 provides a detailed list of substitutes for each individual food item.

We also aimed to assess the nutritional implications of those dietary replacements. Specifically, we examined total energy intake and key macro- and micronutrients, including protein, saturated fats, fiber, calcium, sodium, iron, zinc, and vitamin B12. These nutrients were selected because they are often highlighted as potential dietary concerns, specifically in plant-based diets. The CIQUAL nutrient composition database was consulted to obtain the nutrient composition data of each food product. (ANSES. CIQUAL) The nutrient composition of new recipes created for the scenario analysis was assessed based on the ingredients used. For certain food products whose nutrient composition was not fully detailed in the CIQUAL database, the information was sourced from Nutritics v6.01, a European nutritional software. (Nutritics® Research Edition v6) CIQUAL was prioritized because Agribalyse is based on this source, thus ensuring consistency in underlying assumptions. A detailed list of the food items for which some nutrient data were retrieved from Nutritics can be found in Supplementary Table 4.

The total energy and nutrient intake of Spaniards in 2022 was estimated by aggregating the caloric and nutrient content of all food products consumed. To identify potential nutritional gaps, we calculated the per capita daily intake based on the population of 46,000,345 Spanish residents, as reported in the 2022 national demand surveys, and compared it to the World Health Organization's (WHO) daily recommendations (The Diet Impact Assessment model, 2023). Since nutritional needs vary by age and sex, WHO's guidelines were specifically tailored to Spain's demographic structure. We recalculated the energy requirements provided by the WHO for a sedentary society like Spain's, as the WHO originally considered a physically active population (EFSA Panel on Dietetic Products, 2013). This adjustment aligns with data from the Spanish National Health Survey, which indicates that a large proportion of the population does not meet the recommended levels of physical activity (Ministerio de Sanidad, 2019).

2.3. *Life cycle impact assessment*

The IMPACT World + v2.1 method (IW+) was selected to characterize the environmental human health burden as it is one of the most recent and globally regionalized life cycle impact assessment (LCIA) methods available and because of its focus on endpoint/damage indicators (Agez et al., 2024; Bulle et al., 2019). Health damage was quantified using the endpoint indicator "Human Health", expressed in DALYs, which accounts for both years of life lost and years lived with disability on a global population level.

The impact categories used in IW + for assessing the human health burden included climate change, ozone layer depletion, human toxicity (both carcinogenic and non-carcinogenic), particulate matter formation, ionizing radiation, photochemical oxidant formation, and water use. For this analysis, water use-related impacts were excluded because the water flow data was not mass balanced for certain LCIs in Agribalyse, which hindered accurate estimates of water-related impacts. IW + effectively models the contributions of these environmental impact categories to a common human health endpoint metric, i.e., DALYs, by examining the related, specific pathways through which environmental changes affect health over both the short and long term. The health outcomes considered include cardiovascular disease, malnutrition, malaria, diarrhea, flood-related consequences, various types of cancer, toxicity, cataracts, hereditary effects, and respiratory conditions. Supplementary Table 5 details the health outcomes attributed to each impact category.

The ReCiPe 2016 v1.1 method was applied as a sensitivity analysis to test the influence of choosing one LCIA method over another (Huijbregts et al., 2017). Among the three cultural perspectives and weighting approaches included in this method, the hierarchist perspective was utilized, which aligns with common policy principles regarding timeframes and other considerations. ReCiPe 2016 was selected as it allows for damage assessment and due to its widespread acceptance and application within the LCA community. For the health damage assessment, similar environmental categories and human health outcomes as those used in IW+ were considered (see Supplementary Table 5). Supplementary Table 6 presents the number of substances accounted for in each method used in this study.

All data was processed using Simapro v9.6.0.1.

2.4. *Interpretation supported by statistical analysis*

Descriptive statistics were used throughout the study to support the interpretation of the environmental human health burden. We compared the impact of food items across specific food categories, evaluating them either by weight or by protein content. Due to the non-normality of the data distribution of some variables—assessed using the Shapiro–Wilk test— we employed non-parametric methods. Specifically, the Kruskal-Wallis test was conducted, followed by multiple comparisons using the Dwass-Steel-Critchlow-Fligner post-hoc analysis, which revealed significant differences among categories (p-value <0.05). Statistical analyses were performed with Jamovi version 2.3.

3. Results and discussion

3.1. *Environmental human health damage from food items*

Fig. 2 illustrates that the meat and fish products had the highest environmental human health damage per kilogram, with no significant difference between them (see Supplementary Table 7 for detailed descriptive statistics and Supplemental Table 8 for statistical differences among food categories per kilogram). These categories exhibited a median (minimum-maximum) damage of 73 (10–223) and 64 (14–333) μDALYs per kg, respectively. The food categories with the lowest median μDALYs per kg were all plant-based, such as vegetables (7 (3–22)), fruits (7 (3–17)), legumes (5 (2–15)), non-alcoholic drinks (4 (0.3–43)), and plant-based alternatives (4 (3–15)). Similarly, among protein foods, the environmental human health impacts of meat and fish were significantly greater than those of legumes when compared on a per-protein-content basis (see Fig. 1, Supplementary Table 9 for detailed descriptive statistics and Supplementary Table 10 for statistical differences among food categories per protein content). The median environmental human health damage per 100g of protein was 32 (5–170), 31 (7–86), 24 (21–30), and 7 (3–17) μDALYs for fish, meat, eggs, and legumes, respectively.

Notably, there was substantial variability within the food categories of meat, fish, cakes, bakery and chocolate goods, ready-to-eat, dairy products, and non-alcoholic drinks. The highest environmental human health damage within these categories was associated with ruminant meats (i.e. beef and lamb); crustaceans, and fish caught via bottom trawling (i.e., cod, anglerfish, haddock, dogfish, whiting) or from aquaculture (i.e, European bass, turbot) including extensive ponds (i.e., pangasius); chocolate-containing products (e.g., chocolate bar, brownie); ready-to-eat meals containing meat or fish (e.g., chili with

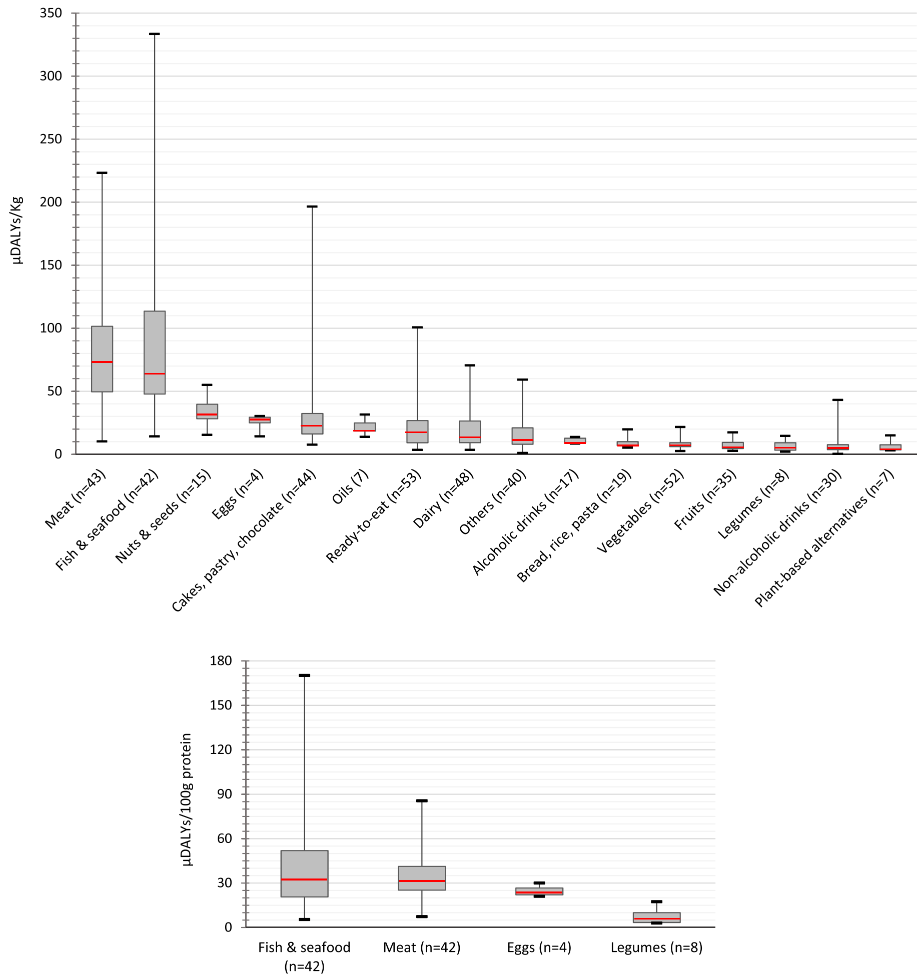

Fig. 2. Environmental human health damage per kilogram (top graph) and per unit of protein content (bottom graph) across food groups, assessed via Life Cycle Assessment using IMPACT World + v2.1 characterization model.
DALY: Disability-Adjusted Life Years.
The box represents the interquartile range (Q1 to Q3), with the red line inside indicating the median. The whiskers extend to the minimum and maximum values. Food groups are displayed in descending order based on their median value.

carne, fish brandade); cheese and butter; and coffee drinks, respectively (see Supplemental Table 11).

3.2. *Environmental human health damage linked to total food demand*

Our analysis revealed that the health damage resulting from the environmental impact associated with Spain's annual food demand in 2022 amounted to 447,152 DALYs, with the vast majority (95 %) stemming from food consumption. Food waste accounted for less than 5 % of the total DALYs (Fig. 3). The leading environmental category contributing to this health damage was climate change, which was responsible for 77 % of the total DALYs, followed by particulate matter at 16 % (Fig. 3).

3.3. *Food groups mainly contributing to dietary environmental human health damage*

Focusing on food consumption, the main contributors to environmental human health impacts were animal-sourced foods, particularly meat (29 %, 123,419 DALYs), fish (16 %, 66,276 DALYs), and dairy products (10 %, 44,502 DALYs) (Fig. 4).

3.4. *Analysis of alternative scenarios*

a. *Environmental human health damage*

As shown in Fig. 5, all analyzed scenarios resulted in reductions in environmental human health damage. Even in the maximum substitution scenario, replacing all red and processed meat with white meat (Scenario 1) led to the smallest reduction among all scenarios (10,349 DALYs, 2 %). In contrast, shifting from meat and dairy to plant-based options (Scenario 2) had a much greater impact, reducing DALYs by 67,921 (15 %) in the 50 % substitution scenario and by nearly one-third in the case of maximum substitution (135,843 DALYs, 30 %). Avoiding consumer food waste (Scenario 3) also showed significant potential, with reductions of up to 20,698 DALYs (5 %) in the most ambitious scenario. Combining a 50 % reduction in meat and dairy consumption with a 50 % decrease in food waste (Scenario 4) resulted in a total reduction of 78,270 DALYs (18 %), while fully implementing both measures yielded the greatest reduction in health impacts, preventing 156,541 DALYs (35 %).

b. *Dietary nutrient intake*

Table 1 shows that Spain's 2022 nutritional situation exhibited both excesses and deficiencies compared to WHO recommendations. Energy, calcium, and zinc intake were slightly above recommended levels, while protein, vitamin B12, saturated fats, and sodium exceeded guidelines. In contrast, fiber and iron intake were insufficient. The contribution of the food groups to each nutrient intake can be found in the Supplementary Table 12. Compared to the baseline, Scenario 1—where red and

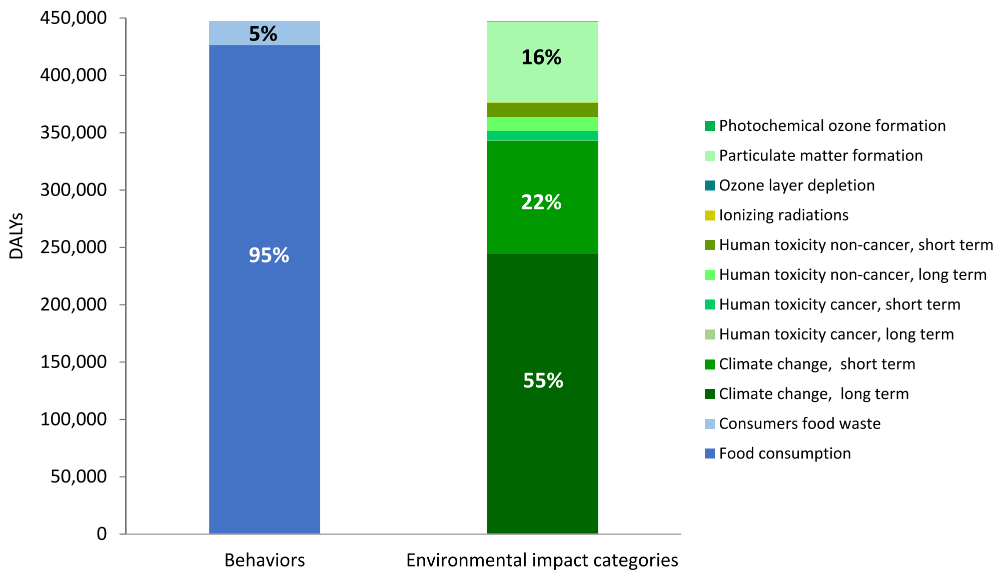

Fig. 3. Environmental human health damage of food demand in Spain in 2022, categorized by consumer behaviors and environmental impact categories. Assessment conducted via Life Cycle Assessment using the IMPACT World + v2.1 characterization model.
DALY: Disability-Adjusted Life Years.
Blue tones represent consumer behaviors, while green tones indicate environmental impact categories.

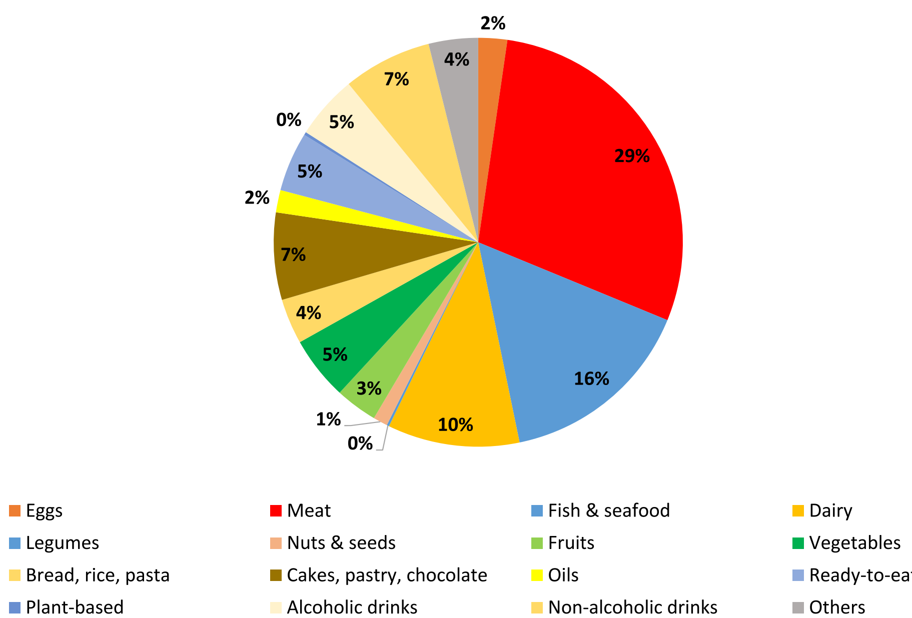

Fig. 4. Proportional contribution (in percentage) of each food category to dietary environmental human health damage, assessed via Life Cycle Assessment using IMPACT World + v2.1 characterization model.

processed meat were replaced with white meat—led to minor but favorable nutritional improvements, primarily reducing saturated fat and sodium intake. More significant changes occurred in Scenario 2, which replaced all meat and dairy with plant-based foods. This shift resulted in lower energy, protein, saturated fat, calcium, sodium, zinc, and vitamin B12 intake while increasing fiber and iron intake. Despite reductions in protein, calcium, and vitamin B12 intake in this scenario, levels remained aligned with WHO guidelines. Zinc intake met recommendations with 50 % replacement but fell slightly below them with 100 % replacement.

3.5. *Sensitivity analysis*

Beyond the intrinsic differences between the LCIA methods, findings from applying ReCiPe 2016 v1.1 remained consistent with those from our primary method (IW+). First, both analyses identified meat and fish as the food categories with the greatest environmental human health damage both per unit of weight and per unit of protein. Conversely, plant-based options exhibited the lowest impact under both functional units (Supplementary Fig. 1 and Supplementary Tables 7–11). Second, both methods highlighted the dominant role of food consumption relative to food waste, with similar contributions (~95 % vs. ~5 %, respectively) (Supplementary Fig. 2). Third, both climate change and particulate matter were identified as the primary environmental

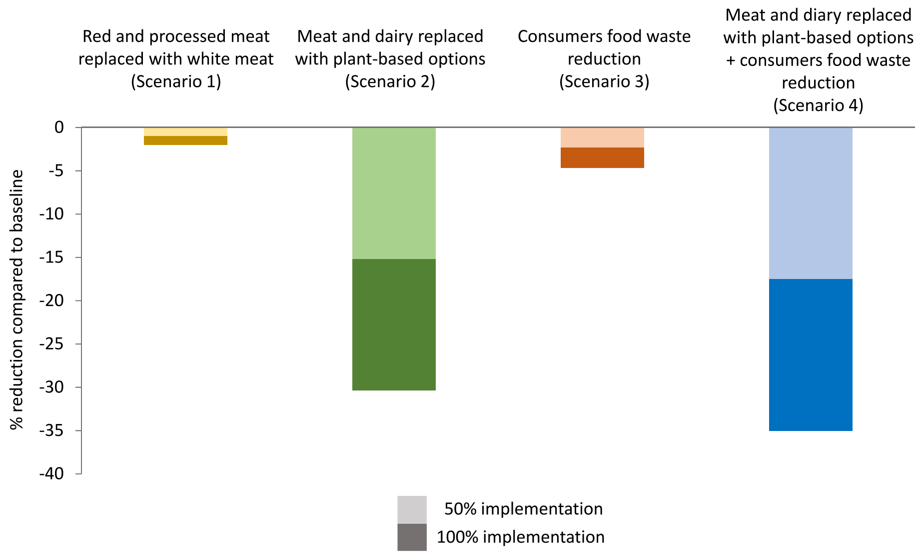

Fig. 5. Percentual reductions in the environmental human health damage of food demand in Spain under alternative scenarios, assessed via Life Cycle Assessment using IMPACT World + v2.1 characterization model.
The baseline represents the actual food demand in Spain during 2022, while the alternative scenarios reflect different dietary and food waste reduction strategies. In each scenario, the lighter color represents the percentual reductions under the less ambitious change (50 % change), while the total height of the lighter and darker sections represents the outcome under a more ambitious change (100 % change).

Table 1
Nutrient intake across different scenarios, with the baseline representing per capita daily nutrient intake in Spain in 2022.

	Daily intake recommendation	Scenarios				
		Baseline	Red and processed meat replacement with white meat (Scenario 1)		Meat and dairy replacement with plant-based options (Scenario 2)	
			50 %	100 %	50 %	100 %
Energy (kilocalories)	1942	1985	1978	1970	1930	1875
Protein (g)	52.8	73.4	74.5	75.5	62.9	52.4
Saturated fats[a] (g)	23.5	26.6	25.8	25.0	23.0	19.4
Fibre (g)	29.6	16.7	16.6	16.6	22.7	28.8
Calcium (mg)	520.0	717.3	718.5	719.7	660.0	602.7
Iron (mg)	16.8	8.5	8.5	8.4	9.2	9.9
Sodium[a] (mg)	2000	3188	3040	2893	2988	2788
Zinc (mg)	6.0	7.8	7.4	7.1	6.7	5.5
Vitamin B12 (μg)	2.3	4.8	4.6	4.4	3.7	2.7

Daily intake recommendations were derived from those established by the World Health Organization, considering the age and sex distribution of the Spanish population.
[a] The values reported for saturated fats and sodium are maximum tolerable levels.

categories contributing to human health damage, although their relative contributions differed compared to the primary analysis (climate change: 38 %, particulate matter: 46 %) (Supplementary Fig. 2; Annex 1 provides a discussion regarding this discrepancy). Fourth, meat, fish, and dairy products were consistently identified as the primary contributors to dietary environmental human health damage, collectively accounting for approximately 60 % of the total impact (Supplementary Fig. 3). Lastly, the percentage of DALYs avoided in the scenario analysis remained comparable across both LCIA methods (Supplementary Fig. 4).

3.6. Results in context

This study is the first to quantify the human health damage linked to the environmental footprint of food demand in Spain. On a per-weight basis, meat and fish showed substantially higher environmental health impacts than plant-based foods, with a particularly high human health burden per unit of protein compared to legumes. The environmental impacts of food demand led to an estimated loss of 447,152 DALYs in 2022, with 95 % attributable to food consumption and 5 % to food wasted by consumers. Animal products—especially meat, fish, and dairy—were the largest contributors to the diet-related environmental human health effects. The findings indicate that replacing meat and dairy with plant-based options and reducing food waste could prevent up to 35 % of these DALYs while also promoting a more nutritionally balanced diet, likely also reducing the direct human health impacts related to food consumption. These results remained consistent across sensitivity analyses, underscoring the robustness of the conclusions.

Over the past few years, a growing number of studies have aimed to quantify the human health burden associated with the environmental impacts of food products and dietary patterns. Table 2 provides a summary of these key contributions. While the scope, methodologies, and underlying assumptions differ considerably across publications, the existing evidence tends to converge on similar conclusions. The substantial environmental impact of meat and certain dairy products (such as cheese) (Poore and Nemecek, 2018; Fresan and Sabate, 2019; Clark et al., 2022), coupled with their high consumption levels—particularly in high-income countries—has prompted recommendations to reduce their intake for the sake of a food system that operates within planetary boundaries (Willett et al., 2019; Romanello et al., 2022; IPCC, 2019; UK Health Alliance for Climate Change, 2024). Emerging research quantifying the health consequences of such dietary shifts supports the idea that environmental gains can also lead to notable benefits for human health. Evidence of these health co-benefits has been documented worldwide, with studies supporting this measure at national (Domingo et al., 2021; Liu et al., 2021; Stylianou et al., 2021; Filippin et al., 2023), regional (Springmann et al., 2023; Walker et al., 2019), and global scales (Springmann et al., 2023).

The adoption of more plant-based diets is unlikely to raise any nutritional concerns in Spain. Conversely, those dietary patterns would be more closely aligned with nutritional recommendations. The slightly insufficient zinc intake in the scenario where meat and dairy are completely replaced can be effectively addressed by following other

Table 2
Summary of studies evaluating environmental human health impacts of dietary patterns or foods.

Study (Author, Year)>	Country/ Region	Scope	Health impact method	Indicator	Key findings
This study	Spain	• Food demand in Spain (2022) • 397 foods • 4 diet/waste scenarios	IMPACT World + v2.1; ReCiPe 2016 v1.1 (Hierarchist approach), sensitivity)	DALYs (LCA endpoint)	• Meat and fish had the highest DALYs per mass and protein units. • 447,152 DALYs linked to food demand in 2022. • 30–35 % potentially avoidable by replacing meat and dairy with plant-based products and reducing food waste.
Springmann et al., 2023	Global, regional	• Dietary shifts from current diets to more plant-based patterns • 13 food groups	Exposure–risk assessment based on Global Burden of Disease (2017) framework	Air pollution ($PM_{2.5}$ and ozone)–related premature mortality	• Plant-based diets could reduce premature mortality by 3–6 % globally. • Reductions up to 21 % in Europe, 18 % in North America, 10 % in East Asia. • Greatest benefits from total avoidance of animal products. • Meat and dairy major contributors to air pollution–related mortality.
Domingo et al., 2021	USA	• Agricultural production: 95 commodities and 67 food products	LCA + spatial emissions data; input into 3 models (APEEP, EASIUR, Intervention Model)	Air quality–related mortality	• ~15,875 annual deaths linked to food production. • 80 % attributable to animal-based foods. • Shift to plant-based diets could reduce mortality by 68–83 %. • Red meat caused highest impacts across multiple metrics. • 5 % reduction achievable by halving food waste.
Walker et al., 2018	Europe	• Food4Me dietary patterns	ReCiPe 2016 v1.1 (Egalitarian approach)	DALYs (LCA endpoint)	• Individual food choices associated with 2.4 ± 1.3 DALYs/person. • Red/processed meats and dairy had the highest DALYs; plant-based diets the lowest.
Stylianou et al., 2021	USA	• 167 food products	IMPACT World + v1.0	DALYs (LCA endpoint)	• Processed and red meats had the highest DALYs per serving. • Fish and seafood in the mid-to-high range. • Dairy also contributed notably. • Fruits, vegetables, legumes, grains, nuts, and seeds had the lowest DALYs.
Liu et al., 2021	China	• Trends in diets (1980–2010) • Modeled shifts to less meat-intensive diets	$PM_{2.5}$ concentration–response functions with the GEMM	$PM_{2.5}$-attributable mortality	• ~5 % of 1.83 million premature deaths in 2010 linked to dietary changes since 1980. • ~75,000 deaths could be avoided by shifting to a recommended less meat-intensive diet. • 75 % of health damage linked to meat and animal feed production.
Filippin et al., 2023	Italy	• Comparison: Vegan vs. Mediterranean diets	ReCiPe 2016	DALYs (LCA endpoint)	• Vegan diet reduced environmental DALYs by 45 % vs. Mediterranean diet. • Meat and dairy key drivers of health-related environmental damage. • Global warming and particulate matter were main contributing impact categories.

DALYs: Disability-Adjusted Life Years; LCA: Life Cycle Assessment; $PM_{2.5}$: fine particulate matter with a diameter ≤2.5 μm; GEMM: Global Exposure Mortality Model; APEEP: Air Pollution Emission Experiments and Policy model; EASIUR: Estimating Air pollution Social Impact Using Regression model.

health-oriented dietary recommendations. For instance, increasing the intake of zinc-rich nuts and seeds (such as pumpkin seeds) could be beneficial. We observed that the actual average daily consumption of these food groups was just 8.5 g—well below the recommended intake of 20–30 g per day. (European Comission) Similarly, promoting the replacement of refined grains with whole grains could further enhance zinc intake. Whole grains are not only higher in fiber but also contain greater concentrations of zinc compared to refined grains. Yet, the data indicated that only 12.5 % of total bread consumption consisted of whole grain bread, highlighting a significant opportunity for dietary improvement. Additionally, replacing meat and dairy with plant-based alternatives would not only lead to a more nutritionally adequate diet but also to improved healthiness. According to Global Burden of Disease, Spaniards currently lose 333,585 DALYs annually due to the high intake of red and processed meats (IHME, 2021). This damage could be eradicated by replacing red and processed meat with white meat. Additionally, this approach could partially reduce the 47,296 DALYs attributed to excessive sodium intake. Furthermore, substituting all types of meat with legumes could produce additional health benefits. This shift would also tackle concerns associated with insufficient legume intake and fiber deficiencies (fiber is only found in plant-based foods). These dietary risk factors are responsible for the loss of 24,898 and 64, 497 DALYs in Spain, respectively (IHME, 2021). On the other hand, replacing milk with calcium-fortified soy drinks could further improve cardiometabolic health outcomes (Erlich et al., 2024). Calcium bioavailability is not a concern, as research has shown to be similar in both milk and fortified soy-based alternatives (Zhao et al., 2005). Nevertheless, more studies evaluating the health effects of other plant-based dairy alternatives are needed (Nájera Espinosa et al., 2024).

Conversely to meat and dairy products, studies focusing on food-related environmental human health damage have frequently overlooked the contribution of fish (Springmann et al., 2023; Domingo et al., 2021). It is essential to consider fish because, besides wide variability, certain species –both wild-caught fish and aquaculture– can cause high environmental damage (Poore and Nemecek, 2018; Gephart et al., 2021). The environmental human health burden of fish identified in this and other studies may be comparable to that of certain meats (Stylianou et al., 2021). For Spaniards, replacing fish with plant-based proteins, along with reducing meat and dairy consumption, could further significantly reduce the environmental human health burden. However, fish consumption is often encouraged rather than restricted in sustainable diet frameworks (Steenson and Buttriss, 2021), primarily due to the recognized health benefits associated with fish-rich dietary patterns (FAO & WHO, 2024). It is important to note that, compared to plant-based proteins such as legumes and nuts, fish does not appear to offer significant additional health benefits (Neuenschwander et al., 2023). Modeling studies suggest that to achieve a more nutritionally balanced and environmentally sustainable diet in Spain, both meat and fish should be at least partially substituted with plant-based alternatives (Muñoz-Martínez et al., 2023; Abejon et al., 2020). The findings of the present study support this recommendation.

Few studies have addressed the potential environmental human health benefits of mitigating consumers' food waste, but previous research conducted in the United States has consistently shown that food waste has only a minor contribution to overall environmental health impacts (Domingo et al., 2021). The present study analyzed exclusively the impact of reducing food waste generated by consumers. The environmental human health impacts of food loss and waste occurring before the consumption stage are included within the food consumption impact assessment, but their impact was not quantified separately. An analysis of all food loss and waste at all life cycle stages would increase the overall contribution of food wastage to the total environmental human health burden. Nevertheless, it is reasonable to expect that this total contribution would still remain below 10 %, given that more than half of food wastage in our context occurs at the consumer level (Eurostat. Food waste and food, 2024). Regardless of the lower proportional contribution, or where food wastage occurs in the food system, addressing food losses and waste across the entire supply chain is essential for developing a comprehensive solution to reduce unnecessary resource use, mitigate environmental pollution, and minimize the associated negative impacts on human health. This is especially important in the context of feeding a steadily growing global population while staying within planetary boundaries (Springmann et al., 2018).

3.7. Strengths, limitations and perspectives

This study is the first to assess the health effects embedded in the environmental impact of food demand by Spaniards, utilizing the well-established LCA methodology, and accounting for both premature mortality and the loss of quality of life. The primary analysis employed the most up-to-date LCIA method for assessing environmental human health effects, while a widely used LCIA method was applied for sensitivity analysis, reinforcing the robustness of our findings. Furthermore, the study encompassed approximately 400 food products modeled with over 600 LCIs and considered a comprehensive range of environmental impact categories. Indeed, although an increasing number of studies are focusing on food-related environmental human health damage, this study can be regarded as one of the pioneering assessments with such a broad scope, as previous studies have typically considered a limited number of food products (Filippin et al., 2023) or environmental impact categories, manly air pollutants (Springmann et al., 2023; Crippa et al., 2022; Domingo et al., 2021).

From an LCA methodological perspective, three key limitations related to LCI data and modeling should be considered: (1) geographical specificity, (2) temporal representativeness, and (3) attributional system modeling. The LCIs used in this study are based on Agribalyse datasets, which reflect the French food system and may differ from the Spanish context in several aspects, such as import sources and electricity mix. The choice of Agribalyse was primarily driven by the need to cover a wide range of nearly 400 food products, each linked to more than 600 LCIs across various stages of the food system. Given the limited availability of Spanish-specific LCI data, Agribalyse remains reasonably representative of Spain and the most comprehensive and suitable option for modeling a national food system that includes both processed and ready-to-eat products. Given the scope of this study, no viable alternative offered comparable breadth and detail. Regarding temporal representativeness, it is reasonable to assume that the analyzed scenarios represent different future scenarios beyond at least a decade since it is unlikely that the modeled behavioral changes for dietary habits take place within only a few years. Such future projections would be better represented by prospective LCI modeling to represent corresponding changes in technology (environmental) legislation, and economy, affecting e.g. electricity production, agricultural practices, and production systems. Consequently, decreased environmental human health impacts could be expected from improved technology and food production practices across all products considered. Additionally, Agribalyse follows an attributional modeling approach. Ideally, our scenario analysis—focused on behavioral shifts that fundamentally alter demand and, consequently, supply—would be modeled using a consequential approach. This would allow for capturing large-scale systemic effects, such as reduced animal production due to lower demand, leading to significant land-use changes (e.g., repurposing agricultural land from animal feed production to food production or conservation efforts to enhance biodiversity and climate resilience), as well as shifts in fertilization practices due to reduced availability of manure. While theoretically feasible, addressing these limitations would require adapting over 600 Agribalyse LCIs to Spanish conditions, converting them into a consequential model, and projecting them into the future of one or several decades to represent the consequences of changes on the future food system in Spain—a task that is currently beyond reach, not only for this study but likely for the broader LCA community. Instead, we assumed a reasonable equivalence between available datasets, with an acceptable impact on the robustness of our findings. This assumption does not affect the core conclusions of our study, particularly as they align with existing literature. In addition to addressing these LCA-related shortcomings, future studies should extend this analysis to other environmental issues with clear links to human health impacts that were not accounted for in our study due to missing impact pathways in current LCIA methods. These gaps include antimicrobial resistance from antibiotic use in livestock farming and the emergence of zoonotic diseases, among others.

Some limitations related to the quality of the analyzed data also need to be acknowledged. In some cases, the data reported in surveys lack sufficient granularity for precise estimation. However, we partially addressed this issue by incorporating different but realistic situations, such as considering a variety of individual food products for general categories and accounting for different cooking methods, aligned with the current Spanish market and culinary traditions. Despite this limitation, the nutrient intake reported in this study aligns with previous findings on dietary patterns in Spanish society (Ruiz et al., 2015, 2016; Samaniego-Vaesken et al., 2017; Olza et al., 2017). On the other hand, and despite relying on official data, self-reported information on food demand and waste may have been influenced by social desirability bias (i.e., individuals tending to report more nutritionally adequate diets), a limitation commonly acknowledged in dietary assessments (Hebert et al., 1995).

3.8. Practical implications of this study

The present study quantified the human health benefits of measures commonly proposed for environmental reasons, highlighting the strong connection between human and planetary health. These findings are valuable for promoting health-conscious dietary practices in Spain. Emphasizing the link between dietary choices and the human health impacts of environmental damage can be a powerful strategy for raising awareness among food policymakers, health professionals, and consumers. Currently, many may overlook the indirect health consequences of dietary choices, often treating environmental impacts as separate from human health (Fresán et al., 2023-). More importantly, these findings could inform the design and implementation of food policies that support the transition toward healthier dietary habits in Spain, considering both direct and indirect benefits to human health.

4. Conclusion

This study emphasizes the strong interconnection between environmental sustainability and human health, showing that actions proposed to reduce environmental degradation are also global and public health strategies. It highlights that public health can be strengthened not only by promoting healthy diets but also by encouraging dietary patterns with low environmental impacts. While educating the population is essential to support these behavioral changes, implementing supportive policies and nudges within public health initiatives is also necessary to facilitate the transition to diets that mitigate both planetary and health crises. Besides the robustness of our findings, further studies should build on this work by using country-specific LCI data, applying consequential and prospective LCA modeling, and expanding the range of health-related environmental impacts considered.

CRediT authorship contribution statement

Ujué Fresán: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Montserrat Núñez:** Writing – review & editing, Methodology. **Inés Valls:** Writing – review & editing, Software. **Ralph K. Rosenbaum:** Writing – review & editing, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.122147.

Data availability

All data have been reported in Supplementary Materials.

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