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Development of the Dietary Pattern Sustainability Index (DIPASI): A novel multidimensional approach for assessing the sustainability of an individual's diet

Joana Margarida Bôto [a,b,c,f,*], Belmira Neto [c,d,e], Vera Miguéis [f], Ada Rocha [a]

[a] GreenUPorto - Sustainable Agrifood Production Research Centre/Inov4Agro, Faculty of Nutrition and Food Sciences, University of Porto, 4150 180 Porto, Portugal
[b] Faculty of Sciences, University of Porto, 4150 180 Porto, Portugal
[c] LEPABE - Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal
[d] ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[e] DEMM - Department of Metallurgical and Materials Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[f] InescTec - Institute of Systems and Computer Engineering, Technology and Science, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal

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ABSTRACT

The adoption of sustainable dietary patterns that consider simultaneously nutritional well-being and reduced environmental impact is of paramount importance. This paper introduces the Dietary Pattern Sustainability Index (DIPASI), as a method to assess the sustainability of dietary patterns by covering the environmental, nutritional, and economic dimensions in a single score. Environmental indicators include carbon footprint, water footprint, and land use, the nutritional quality is evaluated through the Nutritional Rich Diet 9.3 score, and the economic aspects are considered using diet cost. DIPASI measures the deviation (in %) of an individual's diet in relation to a reference diet. The case study utilized dietary data from the Portuguese National Food, Nutrition, and Physical Activity Survey (IAN-AF 2015–2016), which included 2999 adults aged 18 to 64. The Portuguese dietary patterns (covering 1492 food products consumed), were compared against the reference Mediterranean diet. Results indicated that the Portuguese dietary pattern had a higher environmental impact (CF: 4.32 kg CO2eq/day, WF: 3162.88 L/day, LU: 7.03 m^2/day), a lower nutritional quality (NRD9.3: 334), and a higher cost (6.65 euros/day) when compared to the Mediterranean diet (CF: 3.30 kg CO2eq/day, WF: 2758.84 L/day, LU: 3.67 m^2/day, NRD9.3: 668, cost: 5.71 euros/day). DIPASI reveals that only 4% of the sample's population does not deviate or presents a positive deviation ($> -0.5\%$) from the Mediterranean diet, indicating that the majority of Portuguese individuals have lower sustainability performance. For the environmental sub-score, this percentage was 21.3%, for the nutritional sub-score was 10.9%, and for the economic sub-score was 34.2%. This study provides a robust framework for assessing dietary sustainability on a global scale. The comprehensive methodology offers an essential foundation for understanding and addressing challenges in promoting sustainable and healthy dietary choices worldwide.

1. Introduction

The global food system is undergoing significant transformations driven by the need to address a multitude of challenges, including climate change, resource depletion, and public health concerns (Liu et al., 2024). With the global population projected to reach nearly 10 billion by 2050, the challenge of providing nutritious food for all while preserving the planet's resources becomes ever more pressing (Giller et al., 2021). Simultaneously, the double burden of malnutrition remains a significant global public health challenge and is characterized by the coexistence of undernutrition and overnutrition within the same population across the life course (Shrimpton and Rokx, 2012). The prevalence of double burden of malnutrition is rising worldwide requiring a shift towards more sustainable and healthful dietary patterns (Tilman and Clark, 2014). In this context, the sustainability of diets has emerged as a critical area of focus.

Sustainable diets are those that achieve a balance between providing

* Corresponding author at: Sustainable Agrifood Production Research Centre/Inov4Agro, Faculty of Nutrition and Food Sciences, University of Porto, 4150 180 Porto, Portugal.

E-mail address: up202000499@edu.fcna.up.pt (J.M. Bôto).

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Nomenclature

Acronyms

AI	Adequate Intake
CF	Carbon Footprint
DIPASI	Dietary Pattern Sustainability Index
Econ	Economic Dimension
Env	Environmental Dimension
LU	Land Use
MRV	Maximum Recommended Value
NRD9.3	Nutrient-Rich Diet 9.3 Score
RDV	Recommended Daily Value
WF	Water Footprint

Symbols

DIPASI i	Dietary Pattern Sustainability Index of individual (i)
MDV k	Maximum Daily Values (MDV) for the limiting nutrient (k)
Nutrient k	Individual's intake of the limiting nutrient (k)
Nutrient n capped	Individual's nutrient intake limited to the Recommended Daily Values (RDV) for the promoted nutrients (n)
PRI	Population Reference Intake
RDV n	Recommended Daily Values (RDV) for the promoted nutrients (n)
SSi,j	Sub-Score (SS) for an individual (i) in a specific dimension (j)
Xi,j	Individual's value (i) for a specific indicator (X) and dimension (j)
Zj	Reference value for a specific indicator (Z) and dimension (j)

essential nutrients, minimizing environmental impact, and being economically viable and culturally acceptable. The Food and Agriculture Organization (FAO) defines sustainable diets as those with low environmental impacts that contribute to food and nutrition security and to healthy life for present and future generations. These diets are protective of biodiversity and ecosystems, culturally acceptable, accessible, economically fair, and affordable, while optimizing natural and human resources (FAO, 2012). This concept reveals the multifaceted aspects of diet sustainability, embracing environmental, nutritional, sociocultural, and economic dimensions.

The environmental sustainability of diets involves minimizing the environmental impact of food production and consumption. This aspect is primarily evaluated through metrics such as greenhouse gas emissions, land use, water use, and biodiversity impact (Jones et al., 2016; Ran et al., 2024). Nutritional sustainability involves promoting diets that meet the nutritional needs of the population, providing adequate vitamins, minerals, and other essential nutrients while avoiding excessive intake of harmful substances like saturated fats, sugars, and sodium. Nutritional quality is vital for preventing diet-related diseases and promoting overall health (Willett et al., 2019). Economic sustainability involves ensuring the affordability and accessibility of healthy, sustainable food choices (Johnston et al., 2014). Economic factors such the food price and income do influence people's food choices and could affect personal nutrition status and health (Lo et al., 2009). Policies promoting subsidies for sustainable foods, incentivizing local production, and reducing food waste are crucial for economic feasibility and equity (Manzoor et al., 2024). Social sustainability includes fair labor practices, supporting rural livelihoods, and preserving cultural dietary traditions. Sustainable food systems should respect the rights and well-being of everyone in the food production process, ensuring fair wages, safe working conditions, and gender equity, while also being culturally adaptable to diverse dietary practices and preferences (Nicholls and Drewnowski, 2021).

The interplay between these dimensions makes the sustainability of diets a complex and multifaceted issue (Downs et al., 2020). Changes in one dimension can have cascading effects on the others. For instance, promoting a diet with a low environmental impact might not always meet nutritional requirements or be economically accessible (Mazac et al., 2024).

Given the complexity of dietary sustainability, a multidimensional assessment approach is recognized as essential (FAO., 2015). In this sense, the present study aimed to develop a composite indicator, the Dietary Pattern Sustainability Index (DIPASI), that evaluates the sustainability of diets by assessing it against a specific reference diet. Additionally, as a case study, the sustainability of the current Portuguese dietary pattern of the adult population (18–64 years) was assessed using DIPASI, and the Mediterranean diet (MDiet) was chosen as the reference diet due to its widely recognized health benefits, sustainability, and cultural relevance (Berry et al., 2015; Braz et al., 2015; Willett et al., 1995). The DIPASI combines in a single index three environmental indicators (carbon footprint - CF, water footprint – WF, and land use - LU), one nutritional indicator (Nutrient Rich Diet 9.3 score - NRD9.3), and one economic indicator (diet cost). Some methodological aspects combined in DIPASI turn it an innovative approach and will be described in detailed in the Methods section. Briefly, DIPASI uses a) relative weights are assigned to environmental dimension indicators based on recommendations from the European Commission (Sala et al., 2017); b) indicators data for each food item, covering a total of 1492 food items. This extends beyond earlier studies in which sustainability assessments relied on a limited set of food groups, without considering the large variability of different food items within the same group (Trijsburg et al., 2020; van de Kamp et al., 2018); and c) a reference diet for the estimation of the sustainability score, providing a standardized and objective benchmark for assessing the sustainability of an individual's dietary pattern.

2. Literature review

The sustainability of diets has garnered increasing attention due to the urgent need to address global environmental challenges, public health issues, and socio-economic disparities. This literature review summarizes the initiatives used to create sustainability indices, discusses the integration of environmental and nutritional assessments, and identifies gaps in current indicators.

In the past 10 years, studies assessing the sustainability of different dietary patterns have been conducted (Naja et al., 2018; Rosi et al., 2017; Sáez-Almendros et al., 2013). Conversely, they generally assess only one dimension of sustainability, or when two or more sustainability dimensions are assessed, only one indicator per dimension is used (Bôto et al., 2022). Furthermore, assessing the sustainability of dietary patterns is very complex, requiring a comprehensive and integrated approach that includes multiple indicators and dimensions. Evaluating diets based on the environmental, nutritional, and socioeconomic dimensions of food consumption was considered a promising approach for promoting sustainable food systems (FAO and WHO, 2019; Mensah et al., 2023).

In recent years, there has been significant advances in the integration of environmental and nutritional assessments within life cycle assessments (LCA) of food systems. A key resource in this domain is the FAO's guide "Integration of Environment and Nutrition in Life Cycle Assessment of Food Items: Opportunities and Challenges" (McLaren et al., 2021). This guide offers a framework for combining nutritional and environmental aspects in LCA, emphasizing the inclusion of diverse environmental indicators with nutritional metrics for a comprehensive sustainability assessment. It provides best practices and recommendations for integrated assessments, aiding informed decision-making by policymakers and stakeholders, while addressing the complexities of considering both nutrition and environmental impacts (McLaren et al., 2021).

Another trend has been the optimization of sustainable diets to balance nutritional content with environmental and economic impacts (Wilson et al., 2019). Efforts have been made to improve environmental impact with minimal dietary changes, aiming to enhance acceptance. For instance, Rocabois et al. (2022) developed INDIGOO, a tool for designing diets that meet individual nutritional needs and population-level environmental targets with minimal dietary changes. Eustachio Colombo et al. (2024) used linear programming to create nutritionally adequate, health-promoting, and climate-friendly diets for the Swedish population. Tompa et al. (2022) used linear programming-based step-wise optimization to lower Hungary's water footprint, showing substantial environmental benefits from moderate dietary shifts.

Additionally, recent studies propose composite indicators (or indexes) to evaluate the sustainability of dietary patterns, combining more than one indicator and dimension to yield a final score of sustainability (Esteve-Llorens et al., 2020b; Garcia-Alvarez-Coque et al., 2021; Trijsburg et al., 2020). Conversely, the methodologies used vary among the proposed indexes. Garcia-Alvarez-Coque et al. (2021) used the Analytical Hierarchy Process (AHP) that propose weights for each evaluated criterion (environmental, nutritional, and social dimensions). Esteve-Llorens et al. (2020b) applied linear programming tools, in particular Data Envelopment Analysis (DEA), to evaluate the relative efficiency of homogenous entities, in this case, the dietary habits of the Spanish average citizen integrating nutritional (Nutrient Rich Diet 9.3 index – NRD 9.3), environmental (carbon footprint) and socio-economic criteria (number of deaths due to tumors of the digestive system, obesity-related health expenditure, and number of persons with food shortages). The Sustainable Diet Index developed by Seconda et al. (2019) includes seven indicators categorized into four standardized sub-indexes, respectively, environmental, nutritional, economic, and sociocultural, and the computation of the index used the population quintile values as the cut-offs. The Sustainable Diet Index by Fresán et al. (2020b) assesses nutritional quality, environmental impact, and economic affordability in cohort studies, and associates them with mortality risk. Lukas et al. (2016) developed the nutritional footprint trying to create a methodological combination of nutritional and environmental indicators in one footprint tool. Masset et al. (2014) evaluated the associations between environmental impact, nutritional quality, and economic costs of foods in a typical French diet. The authors assessed each of these three parameters to compose a sustainability score for 363 foods systematically selected from a national cross-sectional dietary survey in France. Strid et al. (2021) used an integrated assessment of nutrition (Nutrient Rich Foods (NRF) index) and climate impact (GHG emissions) of foods. Stylianou et al. (2016) developed a combined nutritional and environmental Life Cycle Assessment (CONE-LCA) framework that evaluates and compares in parallel the environmental (global warming and respiratory inorganics) and nutritional effects (Disability Adjusted Life Years – DALYs) of foods or diets. Tepper et al. (2021) developed a questionnaire to measure and score sustainable and healthy eating, the Sustainable-HEalthy-Diet (SHED) Index, with questions focusing the consumption of sweetened beverages and bottled water, the consumption of ultra-processed food and plant-based foods, the purchase of organic food and food consumerism, including food waste and domestic waste streams. Panzone et al. (2013) designed an Environmentally Sensitive Shopper (ESS) index for sustainable food consumption that account for the environmental impact (carbon footprint) of the quantity and composition of food consumption at home.

A scoping review from Neta et al. (2023) brings an overview of the sustainable diet indices that have been developed based on the EAT-Lancet Commission. Trijsburg et al. (2020) developed the WISH Index to score the healthiness and the environmental impact of diets, using the EAT-Lancet recommendations (based on existing systematic reviews) for classifying the 13 food groups as protective, neutral, or to limit. Knuppel et al. (2019) developed the EAT-Lancet Diet Index (ELD-I) to investigate the association between the EAT-Lancet diet score and major health outcomes. Llanaj et al. (2021) examined adherence to various dietary patterns, including the EAT-Lancet and DASH diets, using the Nutrient-based EAT Index (NB-EAT) to study diet quality and related costs. Cacau et al. (2021) proposed the Planetary Health Diet Index (PHDI) based on the EAT-Lancet reference diet to study overall diet quality, carbon footprint, and its association with obesity. Tepper et al. (2021) established the Sustainable-Healthy-Diet (SHED) index as a practical tool to measure healthy sustainable diets. Lastly, Stubbendorff et al. (2022) developed a novel EAT-Lancet Diet Index (EAT) to quantify adherence to the EAT-Lancet diet and its association with mortality.

Although these indexes are based on a multi-criteria approach, for most of them the evaluated dimensions do not always integrate the economic component (Esteve-Llorens et al., 2020b; Lukas et al., 2016; Trijsburg et al., 2020). Furthermore, the type of indicators chosen within the environmental dimension are sometimes insufficient for a comprehensive assessment. For instance, many studies focus primarily on carbon footprint (Esteve-Llorens et al., 2020b; Seconda et al., 2019) while often overlooking other crucial aspects such as water use, which is a fundamental component of the food supply chain. The exclusion of water footprint can lead to an incomplete understanding of the environmental impacts of dietary patterns. Studies by Ridoutt and Pfister (2010) and Hoekstra et al. (2011) highlight the importance of including water footprint to capture the bigger spectrum of environmental impacts.

To conclude, the field of sustainable diet assessment is rapidly evolving, with increasing recognition of the need for comprehensive, multidimensional approaches that integrate environmental, nutritional, and socio-economic indicators. Despite significant advancements, there remain notable gaps and challenges, particularly in achieving standardized methodologies and incorporating a larger spectrum of potential environmental impacts relevant for the food system, such as water use. The development of various sustainability indices highlights the progress made in this area, yet also underscores the necessity for ongoing refinement and validation of these tools.

3. Methods

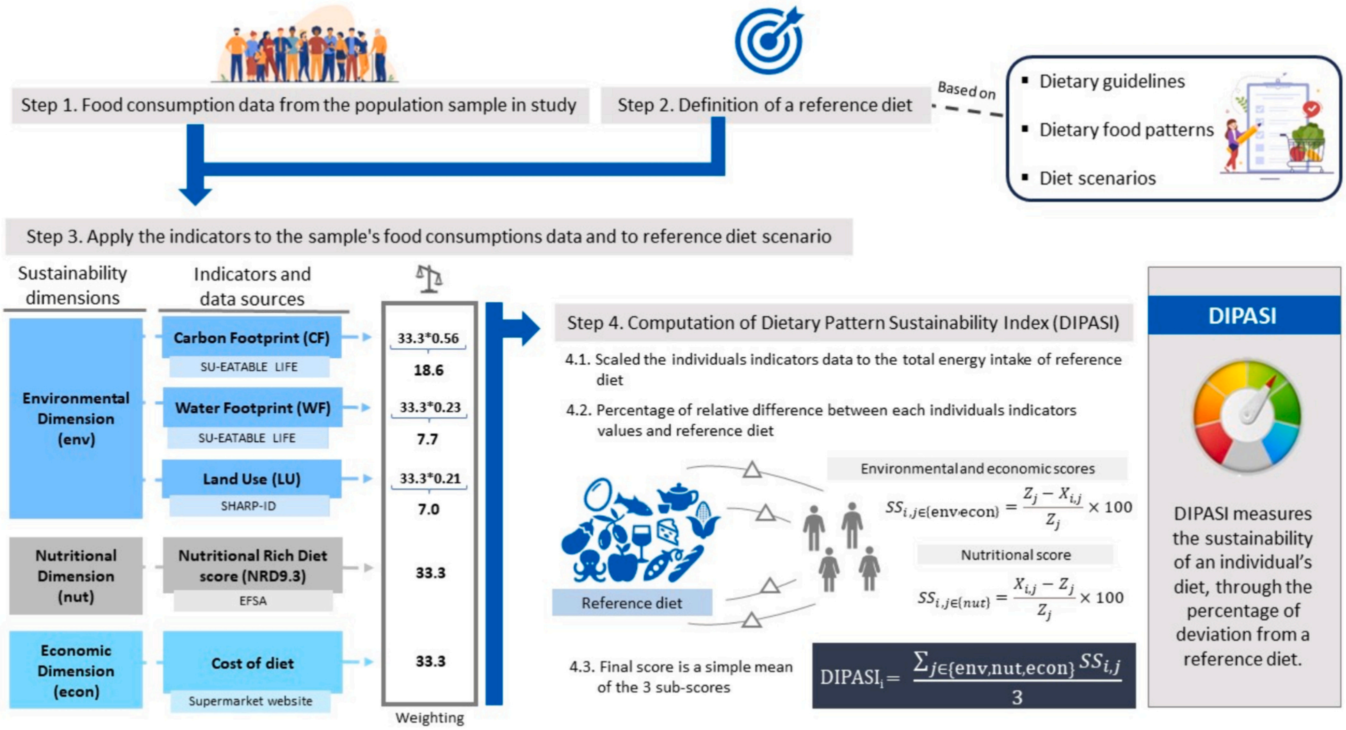
3.1. Development and computation of the Dietary Pattern Sustainability Index (DIPASI)

A novel composite index, the DIPASI, was developed to comprehensively evaluate the sustainability of an individual's diet, focusing on three fundamental dimensions: environmental, nutritional, and economic. DIPASI measures the percentage of deviation from an individual's diet compared to a reference diet. The reference diet will contribute with cut-off values to determine how distant from the reference diet the individuals are. Fig. 1 presents a summary of the methodological approach used to construct DIPASI.

3.1.1. Selection of both the population sample in the study and the reference diet

Firstly, the methodology proposed involves selecting the sample case study, i.e. the population study group. This could be a general population, a specific demographic, or a niche group. For this sample, it is necessary to collect the food consumption data, with detailed information regarding the type and amount of food items consumed by the individuals.

Secondly, the methodology proposed implies reviewing the available literature to identify a reference diet. The revision covers established dietary patterns or dietary guidelines and recommendations. Based on the information gathered the reference diet should be customized and described, in terms of daily energy intake, nutrient content (determining the appropriate levels of macronutrients and micronutrients), food sources (selecting specific foods and food portions), and dietary plan (considering factors like meal frequency, portion sizes, and meal



$$SS_{i,j\in(env\cdot econ)} = \frac{Z_j - X_{i,j}}{Z_j} \times 100$$

$$SS_{i,j\in(nut)} = \frac{X_{i,j} - Z_j}{Z_j} \times 100$$

$$DIPASI_i = \frac{\sum_{j\in\{env,nut,econ\}} SS_{i,j}}{3}$$

Fig. 1. Schematic overview of the methodological approach for the construction of Dietary Pattern Sustainability Index (DIPASI). The DIPASI score is computed averaging the sub-scores (SS) obtained from the nutritional, environmental, and economic assessments. The $SS_{i,j}$ represents the Sub-Score for an individual (i) in a specific dimension (j). $X_{i,j}$ represents the individual's value for a specific indicator, and the Z_j represents the reference value for a specific indicator. $\sum$ – Summation operator; $\in$ – Symbol read as "is an element of".

composition). This documentation is critical for reproducibility and transparency of the methodology used in the research.

The use of a reference diet to obtain the reference values for the estimation of the sustainability score, as opposed to the sample's values (e.g. median values), offers the advantage of providing a standardized and objective benchmark for assessing the sustainability of an individual's dietary pattern. This approach ensures consistency and comparability across different individuals and populations, allowing for a more meaningful and robust assessment of sustainability. By using reference values, we can make evaluations based on an established criterion, making it easier to identify whether an individual's dietary pattern is more or less sustainable in a broader context, rather than relative to their specific population. Sample-based cut-off values, like the median, offer context-specific insights but have notable disadvantages. They lack generalizability, making it difficult to apply findings to broader populations and compare results across studies. Such medians may mislead by not reflecting the true variability of the overall population and are sensitive to sample characteristics, potentially distorting interpretations. Additionally, they complicate benchmarking against standardized measures, obscure the definition of high or low values due to sample variability, and provide only relative measures without indicating performance against external standards.

3.1.2. Environmental, nutritional, and economic assessment of the population sample in the study and the reference diet

3.1.2.1. Nutritional quality assessment. The nutritional quality of the sample chosen is assessed through the NRD9.3 score, introduced by Van Kernebeek et al. (2014). The NRD9.3 score is constructed based on the contrast in consumption between nine nutrients that should be promoted (namely protein, fiber, calcium, iron, magnesium, potassium, vitamin A, vitamin E, and vitamin C), and three nutrients that need to be limited (total sugar, saturated fat, and sodium) (as defined in Eq. (1)). It compares the quantity of nutrients consumed by individuals against established guidelines, thus providing a score based on nutrient density irrespective of the total energetic intake. This approach ensures that the nutritional quality of the diet is assessed based on the adequacy of specific nutrients, rather than the total energy consumed. The nutrients recommended daily values (RDV) and maximum daily values (MDV) could be retrieved from the nutritional guidelines used in the country of study, available in, for example, the European Food Safety Authority (EFSA) recommendations.

$$NRD9.3 = \left(\sum_{n=1}^{n=9} \frac{nutrient_{n,capped}}{RDV\ n} - \sum_{k=1}^{k=3} \frac{nutrient_k}{MDV\ k} \right) \times 100 \tag{1}$$

To avoid crediting the overconsumption of encouraging nutrients, their intakes were capped. Therefore, when the intake of a certain nutrient was higher than its RDV, the intake of this nutrient was set to its RDV (Van Kernebeek et al., 2014).

3.1.2.2. Environmental impact assessment. The environmental dimension is measured through the CF, WF, and LU indicators. These environmental indicators were identified as the most commonly used indicators to assess the environmental dimensions of sustainability (Bôto et al., 2022; Jones et al., 2016). The CF describes the amount of greenhouse gas emissions that a particular food product releases into the environment during its lifetime, and is usually expressed in kg CO_2 eq per kg of food product (Shabir et al., 2023). The water footprint accounts for the volume of freshwater used throughout the entire production cycle of food items, including blue water (surface and groundwater), green water (rainwater stored in the soil), and grey water (water required to assimilate pollutants). This indicator is crucial for understanding the impact of food production on water resources (Hoekstra et al., 2011). The LU, measured in meters squared (m^2) per kilogram of a given product, describes the human use of land (Giacosa et al., 2016).

The databases used for assessing these environmental categories are among the most recent and comprehensive available. CF and WF data can be retrieved from the SU-EATABLE LIFE database (Petersson et al., 2021). This multilevel database follows a standardized methodology to extract information from a large number of recently published and peer-reviewed articles (data from (Clune et al., 2017) is included) and assign carbon footprint and total water footprint (the sum of blue, green and grey water footprints) values to food items. A major contribution to the water footprint data in the SU-ETABLE LIFE database comes from the work of Hoekstra and Mekonnen, ensuring the use of standardized and up well recognized methods capturing the environmental problems associated with water use. They evaluated the green, blue, and grey water footprint of crops and derived crop products (Mekonnen and Hoekstra, 2010b), as well as the water footprint of farmed animal products (Mekonnen and Hoekstra, 2010a). The database provides a reliable science-based tool, ensuring repeatability as a result of its extensive breadth, low cost, and accessibility. The database takes into account life cycle considerations for the food products. The system boundaries considered in the SU-EATABLE LIFE database to assess the environmental dimensions of the food products include the primary production, processing, packaging, transport and retail activities, excluding post-market life cycle phase like for example cooking and food products end of life. The CF and WF data sources in the SU-EATABLE LIFE database cover a geographical distribution from Africa, America, Asia, Europa, and Oceania (Petersson et al., 2021).

LU data can be retrieved from SHARP ID that also a resource that aligns with current best practices in environmental assessment. This database provides an estimation of LU per kg of food as consumed for 944 food items coded with a unique FoodEx2-code of EFSA. The data comprised the stages of primary production, processing, packaging, transport, retail stages, food losses and waste, and food preparations. Foods included in the SHARP ID were based on the reported food intake of the four European countries, specifically Denmark, Czech Republic, Italy and France (Mertens et al., 2019).

The CF per food item is calculated by multiplying the mass (g) of the food consumed by the CO_2 emissions per kilogram (kg) of that specific food. To determine the total daily CO_2 eq. emissions from the diet, the emissions from all the food items are summed up. This total represents the estimated daily CF of either the individual's diet and the reference diet. Similar methodological approaches are used for the WF and LU calculations. For CF and WF calculation it was used the food products' gross weights, while for the LU it was used the raw edible weight.

3.1.2.3. Economic assessment. The chosen economic indicator for this index is the monetary cost of the diet (Euro/day). To estimate the dietary cost of the sample of study and of the reference diet, a food price variable is linked to each food item. Retail prices are obtained by consulting the website of one of the major supermarkets. For consistency, the lowest non-sale price encountered for each food item is selected. The total daily monetary costs of individuals' diets are calculated by multiplying the cost per mass (€/kg) of each food item by the daily quantity consumed.

3.1.3. Computation of Dietary Pattern Sustainability Index (DIPASI)

To eliminate the impact of individuals' diverse daily energy intakes, all indicators are standardized to the same daily energy intake (kcal/day) defined for the reference diet. The next step was the calculation of the relative difference between the indicator's values for each individual in the sample and the indicator's values for the reference diet. Assuming an individual *i* and each dimension considered *j*, the environmental sub-score ($SS_{i,j\ \in\{env\}}$) and the economic sub-score ($SS_{i,j\ \in\{econ\}}$) are calculated by subtracting the individual's values $X_{i,j}$ to the reference Z_j and dividing the result by the same reference value Z_j (Eq. (2)), that is multiplied by 100. This provides the % of relative deviation.

$$SS_{i,j\in\{\mathrm{env,econ}\}} = \frac{Z_j - X_{i,j}}{Z_j} \times 100 \tag{2}$$

For the nutritional sub-score ($SS_{i,j\ \in\{nut\}}$), in order to align the lowest values obtained with reduced sustainability across all dimensions, the difference is calculated by subtracting the reference value from the individual's values (Eq. (3)).

$$SS_{i,j\in\{nut\}} = \frac{X_{i,j} - Z_j}{Z_j} \times 100 \tag{3}$$

For the environmental sub-score a relative weight is assigned for each indicator, according to a technical report from the European Commission's Joint Research Centre (JRC) (Sala et al., 2017). The JRC developed a method for weighting the environmental impact categories according to their relevance to the overall environmental problems. This allows the obtention of one single indicator expressing the overall environmental impact. This method was designed for use in the context of Environmental Footprints, with the primary goal of allowing the aggregation of Life Cycle Assessment (LCA) results into a single score while assigning varying weights to different environmental impact categories. The method's purpose is to weight the Environmental Footprints' impact categories based on their relevance in overall environmental issues. The proposal presents weighting factors for 13 environmental impact categories (excluding toxicity-related impact categories), covering climate change, acid rain, human and eco-toxicity, and particulate matter but also impacts due to the use of water, land, and resources. The climate change, water use, and land use categories were weighted with 22.19%, 9.03%, and 8.42%, respectively. Since these values are the relative weights in a total of 13 categories, for computing DIPASI the proportion of each one was calculated for a total of three indicators in the environmental dimension, corresponding to 56% for the CF, 23% for the WF, and 21% for the LU.

It is important to note that the concept of sustainable diets, as outlined by Burlingame and Dernini (2012), does not prioritize any specific dimension of sustainability over others. Hence, all sub-scores were given equal weight when calculating the DIPASI.

The DIPASI score is then calculated for each individual *i* as an arithmetic mean of the three sub-scores and can range, theoretically, from -infinite to +infinite (as defined in Eq. (4)). DIPASI evaluates the sustainability of an individual's diet, therefore, higher values in the final score, as well as in its sub-scores, reflect higher proximity to the reference values, and possibly lower environmental impact, greater nutritional quality, and a lower diet cost. The reference value of the final score corresponds to a deviation of 0%.

$$\mathrm{DIPASI}_i = \frac{\sum_{j\in\{env,nut,econ\}} SS_{i,j}}{3} \tag{4}$$

In order to characterize the individuals based on their percentage of deviation from the reference, the final score is discretized, grouping the values into nine categories:

- High deviation (negative) $\leq -50\%$;
- Reasonable deviation (negative) $> -50\%$ and $\leq -20\%$;
- Small deviation (negative) $> -20\%$ and $\leq -10\%$;
- Very small deviation (negative) $> -10\%$ and $\leq -0.5\%$;
- No deviation $> -\ 0.5\%$ and $\leq 0.5\%$;
- Very small deviation (positive) $>0.5\%$ and $< 10\%$;
- Small deviation (positive) $\geq 10\%$ and $< 20\%$;
- Reasonable deviation (positive) $\geq 20\%$ and $< 50\%$;
- High deviation (positive) $\geq 50\%$.

Table S19 in the supplementary material provides a detailed step-by-step guide for the creation of DIPASI.

3.2. Case study

3.2.1. Sample population

In this study, the Portuguese Dietary Pattern was used as a case study, and the data was drawn from the National Survey on Food, Nutrition, and Physical Activity (IAN-AF), conducted from 2015 to 2016 (Global Dietary Database, 2022). This period covers the most recent available representative data for Portuguese dietary consumption patterns. The survey aimed to capture a representative sample of the Portuguese general population, spanning from 3 months to 84 years of age. The IAN-AF collected national information on food consumption (including nutritional intake and dimensions of food security and insecurity) and physical activity and its relationship with health determinants, namely socioeconomic factors (Lopes et al., 2017a). Dietary intake was obtained by two non-consecutive 24-h dietary recalls (24-hR) for 12 months to minimize seasonal variability. The data provides detailed information about the quantities of the single different foods products consumed per day and, the intake of macronutrients and micronutrients. The data provides detailed information about the quantities of various food products consumed per day. Even recipes were broken down into their individual food components. The corresponding nutritional information (macronutrients and micronutrients) is also provided at the food level, based on the Portuguese Food Composition Table (INSA, 2007). In the scope of this study, all food intakes were averaged over the two collection days before being used to score individual dietary intakes. The detailed IAN-AF 2015–2016 methodology is in-depth described in the literature (Lopes et al., 2018; Lopes et al., 2017b).

In the present work, out of the selected sample who completed the two interviews, only adults from 18 to 64 years, excluding pregnant and breastfeeding women were considered. In total, this represents a sample of 2999 people.

3.2.2. Reference diet - Mediterranean diet scenario

The reference diet considered for this index is the MDiet. The selection of the MDiet as the reference diet for testing the DIPASI was driven by diverse reasons. The MDiet is renowned for its positive impacts on human health. Extensive research has consistently demonstrated that adherence to this dietary pattern is associated with reduced risks of chronic diseases, including cardiovascular diseases, diabetes, and certain types of cancer (Guasch-Ferre and Willett, 2021; Willett et al., 1995). Beyond its health benefits, by emphasizing the consumption of locally sourced, seasonal, and plant-based foods, the MDiet is associated with a lower environmental impact (BCFN, 2016; Serra-Majem et al., 2020). Several authors argue that the Mediterranean diet, which is primarily plant-based with low animal products consumption, has a lower environmental impact than other dietary patterns. As a result, it features a reduced water footprint, lower greenhouse gas emissions, decreased energy consumption, and less land use compared to other contemporary diets (Burlingame and Dernini, 2011; Dernini et al., 2017; Gussow, 1995; Heller et al., 2013; Sáez-Almendros et al., 2013; Tilman and Clark, 2014). Additionally, the MDiet is part of the intangible cultural heritage of humanity by UNESCO (Medina, 2019). Its deep cultural roots reflect the traditional eating habits and culinary practices of the countries in the Mediterranean region, including Portugal (despite its Atlantic geography, it shares fundamental features with Mediterranean countries, like climate, geography, culture, and eating habits) (Braz et al., 2015).. This cultural relevance underscores its potential for wider acceptance and practical implementation by various populations (Serra-Majem et al., 2012; Serra-Majem and Ortiz-Andrellucchi, 2018). These reasons make the MDiet an appropriate choice for estimating sustainability score, ensuring that our evaluation accurately reflects the principles of a sustainable and healthful food pattern.

The MDiet scenario is based on the Mediterranean diet recommendations taking as reference the Mediterranean food pyramid (Bach-Faig et al., 2011) and the Portuguese Mediterranean diet wheel (Rodrigues et al., 2022). Both provide the frequency of consumption and the recommended portions of food groups and specific food items.

The scenario is defined through the creation of seven food days using different recommended amounts of foods belonging to 11 food categories (fruits, vegetables, pulses, grains, nuts, dairy products, eggs, meat, fish, sweets, and oils). In order to cover the issue of seasonality, fruit and vegetables from different seasons were considered in the construction of the weekly menu plan. The total daily grams, CF, WF, LU, and diet cost for the MDiet scenario were obtained by averaging the values across the seven food days created.

The vertex of the Mediterranean food pyramid presented the sugary and unhealthy fats-rich foods that should not exceed two servings per week. For that reason and taking into account a maximum of 5% of the total daily intake of free sugars preconized by the World Health Organization (WHO, 2015), two options of sweets as a possible substitution of two pieces of fruit in two different food days were considered.

A reference daily energy intake of 2000 Kcal/day was used and is aligned with common dietary guidelines (Gregório et al., 2021). Additionally, to ensure that the reference MDiet met the nutritional recommendations for the adult population (avoiding nutritional deficiencies), we compared the micronutrient levels (vitamin A, vitamin D, Vitamin E, vitamin B2, vitamin B6, vitamin B12, vitamin C, thiamine, niacin, folates, sodium, potassium, calcium, phosphorus, magnesium, iron, zinc) against EFSA guidelines (EFSA, 2023). The EFSA micronutrient recommendations by using the highest value of the Population Reference Intake (PRI) was used as the reference point. If the PRI was not available, we used the Adequate Intake (AI) instead. This approach ensures that the recommendations encompass the needs of both men and women adults. By selecting the higher value of the PRI range, we aimed to cover the nutritional requirements of the entire population, providing a more inclusive and comprehensive guideline for micronutrient intake. Our analysis confirmed that all the micronutrients are in line with the guidelines and that MDiet provides an adequate nutritional intake for both men and women from 18 to 64 years. A more detailed description of the MDiet scenario can be found in Supplementary Material (Table S1 to Table S15).

3.2.3. Assumptions

Concerning the nutritional quality assessment, the recommended daily values (RDV) and the maximum daily values (MDV) for nutrients intake, used to calculate the NRD9.3, were taken from the EFSA recommendations for adults (Table 1). These daily values are specific for life-stage and gender. In our study, we followed the same assumption used to contrast the nutritional adequacy of MDiet against the EFSA guidelines, by using the highest value of the PRI or AI as the reference point.

Table 1
Dietary reference values for qualifying and disqualifying nutrients according to EFSA.

Nutrient	Dietary reference value	Source
Qualifying nutrients		
Protein	57 g	(EFSA, 2012)
Fiber	25 g	(EFSA, 2010)
Calcium	1000 mg	(EFSA, 2015b)
Iron	11 mg	(EFSA, 2015c)
Magnesium	350 mg	(EFSA, 2015d)
Potassium	3500 mg	(EFSA, 2016)
Vitamin A	750 μg	(EFSA, 2015a)
Vitamin C	110 mg	(EFSA, 2013)
Vitamin E	13 mg	(EFSA, 2015e)
Disqualifying nutrients		
Sodium	2000 mg	(EFSA, 2019)
Saturated fat	20 g	(EFSA, 2009)
Total sugar	90 g	(EFSA, 2009)

A total of 1492 food items consumed by the Portuguese sample were confronted with available environmental, nutritional, and economic indicators. The data on individual food consumption and their respective nutritional composition are highly detailed, refined to the specific food consumed, and were obtained from the IAN-AF 2015–2016. This allowed the differentiation of food items between the same food group, for example, between whole and refined grains.

However, environmental databases lacked granularity for some indicators for the distinct types of food products (examples are the different types of cheese consumed by the population). As a result, the environmental assessment covered a total of 435 food items, while information for nutritional and economic evaluation was obtained for all the 1492 food items consumed by the population.

For matching the foods consumed by the Portuguese population with environmental indicators, we assigned food-by-food information available in the databases, using the highest level of refinement possible. For example, in the environmental dimension, the CF, WF, and LU databases allowed for the separation between breakfast cereals, grains (such as rice and wheat), white bread, and whole wheat bread, reflecting the differences between the same foods with different processing levels.

Regarding the environmental impact assessment, when information about the CF for specific food items consumed by the Portuguese population was not available in the SU-EATABLE LIFE database, other sources of information were used, such as the Big Climate database (CONCITO, 2023; Schmidt et al., 2021), the SHARP ID (Mertens et al., 2019), and some articles (see Table S16 in Supplementary Material). Additionally, some methodological assumptions were considered for attributing footprints to the respective food item: a) whenever there was no information on a particular food, the highest value of a food belonging to the same subgroup was used; b) for foods with more than one ingredient and for ultra-processed foods, in the absence of information for that specific food product, it was used the largest single footprint for the overall ingredients composing the food product; c) when the database provides information relating to different commercial presentations of the same food product (example: dry, frozen, fresh) the average value for that product was used; d) the WF of seafood and mineral water were considered as zero (Gephart et al., 2014; Hoekstra et al., 2011).

For the economic assessment, the retail prices were obtained by consulting the website of a Portuguese supermarket chain, the *Auchan*® supermarket. Some methodological assumptions were also considered when assigning the price to the respective food item. In the case of some drinks, such as tea/infusions, and coffee/barley, the following assumptions were considered: a) the unit price of the tea/infusion sachet and coffee capsules; b) the unit price of cafeteria products (espresso coffee, decaffeinated espresso, carioca coffee); and c) the price for the quantity of aromatic plants (3 g)/barks (10 g)/spices (4 g)/roots (10 g) or powder (10 g) required for the preparation of a single serving of beverage, excluding the quantity of water and its impact on the price.

In the computation of DIPASI, to eliminate the impact of individuals' diverse daily energy intakes, we standardized all indicators to a total of 2000 kcal/day, following the rationale of Mediterranean Diet scenario. By aligning all the indicators to a total of 2000 kcal/day, we ensured that the deviations measured by DIPASI were consistent and comparable. Despite the adjustment to 2000 kcal/day, the nutritional evaluation remains focused on the actual nutrient intake relative to nutritional guidelines. The NRD9.3 score ensures that nutrient adequacy is evaluated independently of energy intake, thus maintaining a robust assessment of nutritional quality.

The origin of the environmental and economic data for each of the food items consumed by the Portuguese sample is presented in Table S16 of the Supplementary Material.

3.3. Statistical analysis

Analysis was performed using R version 3.6.1 software. Data were described by absolute and relative frequencies, mean, standard deviation (SD), median, and interquartile range (IQR) whenever appropriate. Spearman's correlation coefficient ($p < 0{\cdot}05$) was applied between the DIPASI sub-scores and aimed to identify associations between sustainability dimensions. Understanding these relationships helps determine if improvements in one dimension (e.g., nutritional quality) affect another (e.g., environmental impact or economic cost). For interpretation of the strength of Pearson's correlation coefficient, the following were considered (Pestana and Gageiro, 2014): $r < 0.2$—very low correlation; $0.2 \leq r \leq 0.39$—low correlation; $0.4 \leq r \leq 0.69$—moderate correlation; $0.7 \leq r \leq 0.89$—high correlation; $0.9 \leq r \leq 1$—very high correlation.

4. Results

4.1. Sample characteristics

The participants (n 2999) were aged between 18 and 64 years old, with a median age of 43 years (IQR 21). Fifty-three percent (n 1573) reported as female and 47% (n 1426) as male. The majority (91.4%, n 2742) lived in an urban area. Regarding Body Mass Index (BMI) categories, 38.8% (n 1165) of the participants had normal weight, 36.1% (n 1083) were overweight, and 24.0% (n 720) were obese.

4.2. Comparison of the Portuguese dietary pattern to Mediterranean diet

The average CF, WF, LU, diet cost, and NRD9.3 of Portuguese dietary pattern (PDP) was, respectively, 4.32 kg CO_2eq/day, 3162.88 L/day, 7.03 m^2/day, 6.65 euro/day and 334. Note that the values for the Portuguese dietary pattern are present in means to align with the means obtained for the MDiet scenario.

In contrast, the MDiet scenario obtained an average of 3.30 kg CO_2eq/day for CF, 2758.84 L/day for WF, 3.67 m^2/day for LU, 5.71 euro/day for diet cost, and 668 for NRD9.3. All the indicators values were lower in the MDiet scenario comparatively to the Portuguese dietary pattern, except for the NRD9.3.

The average daily grams each food group consumed in the Portuguese dietary pattern and in the MDiet scenario are shown in Fig. 2. The Portuguese dietary pattern was characterized by a higher intake (average daily grams) of red meat, white meat, processed meat, cookies/cakes/sweets, and beverages other than water and wine, comparatively to MDiet.

In the creation of the MDiet menus, certain food groups were not included to match the recommendations of MDiet guidelines. Specifically, the menus did not include processed meat, fats other than olive oil, coffee or its substitutes, alcoholic beverages other than wine, and non-alcoholic beverages other than water. Consequently, the values for these food groups appear as zero in Fig. 2, reflecting their intentional omission from the reference Mediterranean diet.

Red meat, dairy products, seafood, and water were the largest contributors to CF of the Portuguese dietary pattern (Fig. 3). Red meat, dairy products, white meat, and cereals/derivatives were the largest contributors to WF. For LU, red meat, white meat, dairy products, and cookies/cakes/sweets were the main contributors. Regarding price, red meat, fruit, seafood, and coffee/substitutes were the main contributors (Fig. 3).

For the MDiet scenario, the contribution of food groups varied. Dairy products, water, seafood, and vegetables were the major contributors to CF. Dairy products, fruits, olive oil, and nuts/seeds were the major contributors to WF. Dairy products, red meat, cereals/derivates, and nuts/seeds were the major contributors to LU. For price, fruits, vegetables, dairy products, and seafood were the major contributors (Fig. 3). NRD9.3 data is not presented in Fig. 3, since this indicator uses information on the total nutrients consumed by an individual and not per food groups.

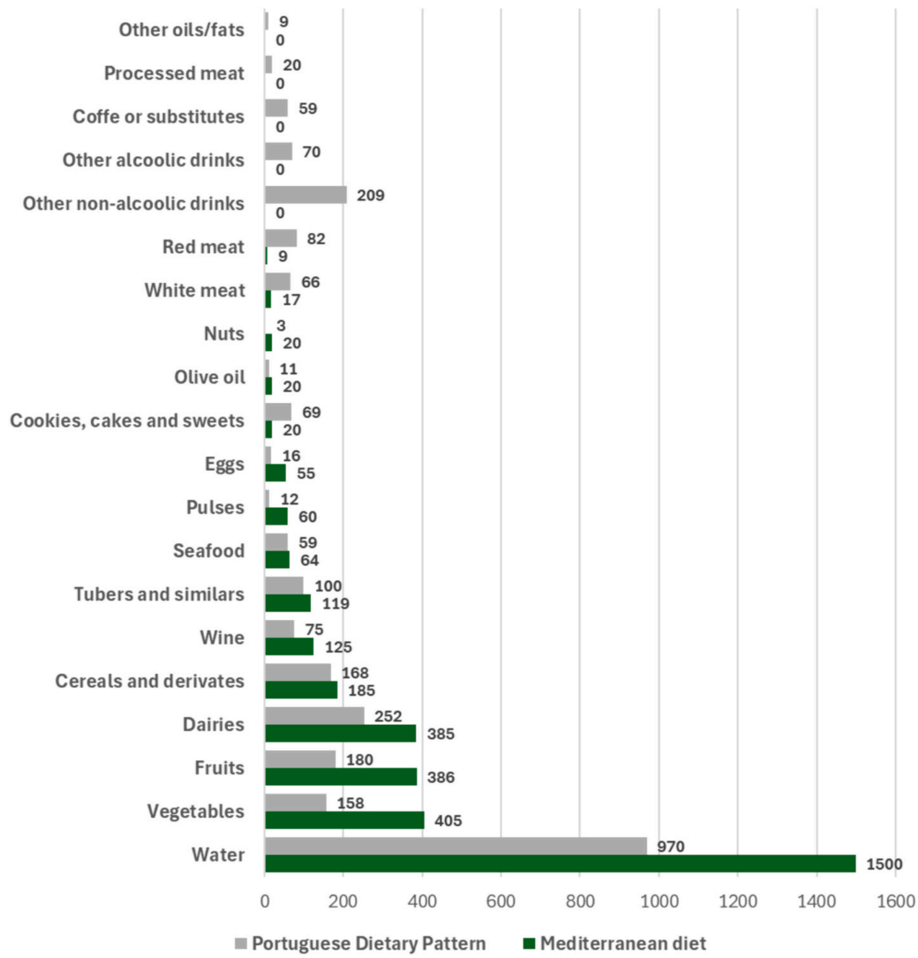


Fig. 2. Daily intake (grams or liters/day) of food groups consumed by the Portuguese adults aged 18–64 years compared to the Reference Mediterranean diet. Values are presented as means.

It is important to note that this information is highly aggregated. For a more detailed examination of the contributions of specific food subgroups within these categories to the total grams, CF, WF, LU, and diet cost, please refer to Tables S17 and S18 in the Supplementary Material.

4.3. Application of Dietary Pattern Sustainability Index (DIPASI)

The distribution of the Portuguese individuals considering DIPASI score, environmental, nutritional, and economic sub-scores are showed in Figs. 4, 5, 6 and 7, respectively. The vertical line in the histograms presents the reference value of 0% of deviation from the reference diet. All the sub-scores and final score presented a predominant prevalence of individuals below the reference values.

The DIPASI histogram summarizes the sustainability score of the Portuguese sample (n 2999), ranging from −224% to 24% relative deviation compared to MDiet. This histogram shows a left-skewed distribution, with a mean deviation of approximately −36.81% (SD 27.71%) and a median deviation of −31.27% (IQR 30.40%). Notably, there is a prominent peak within the range of −25% to −19% deviation from the reference MDiet's sustainability standards. This indicates that a considerable proportion of individuals exhibit a deviation in line with DIPASI's reasonable deviation category (≤20%). Additionally, looking at the number of individuals to the right of the reference line, only 3.96% (n 119) of the individuals present either no deviation or a positive deviation from the reference score value in DIPASI. And a smaller but noticeable group of individuals appears very far from the reference (Fig. 4).

The sustainability sub-scores also exhibit large variability, with some individuals deviating significantly from the reference diet, while others closely aligned with it. Looking at the number of individuals to the right of the reference line, the percentage of no deviation and positive deviation for the environmental sub-score was 16.70% (n 501) (Fig. 5), for the nutritional sub-score it was 8.44% (n 253) (Fig. 6), and for the economic sub-score it was 26.71% (n 801) (Fig. 7). It was observed that the environmental sub-score exhibited a median deviation of −31.22% (IQR 60.33%). The nutritional sub-score displayed a median deviation of −41.76% (IQR 36.89%). For the economic sub-score, the median deviation was −17.71% (IQR 43.15%).

The classification of individuals based on DIPASI categories is illustrated in Fig. 8. A significant proportion of the sample (48.6%) exhibited a reasonable negative deviation, indicating that their scores deviated by 20 to 50% in line with the final score discretization (Section 3.1.3) below the reference MDiet. Only 4% of the sample population showed no deviation or a positive deviation (>−0.5%) from the Mediterranean diet. However, this percentage was higher when considering the sub-scores individually. For the environmental sub-score, 21.3% exhibited no deviation or a positive deviation (>−0.5%). For the nutritional sub-score, this figure was 10.9%, and for the economic sub-score, it was 34.2%.

In terms of the number of sub-scores matching or surpassing the reference values, it was found that the majority of individuals (57.2%, n 1714) did not achieve any score equal to or above the reference. On the other hand, 33.2% (n 996) achieved this for one of the dimensions, 9.4% (n 282) for two dimensions, and a mere 0.2% (n 7) for all three dimensions.

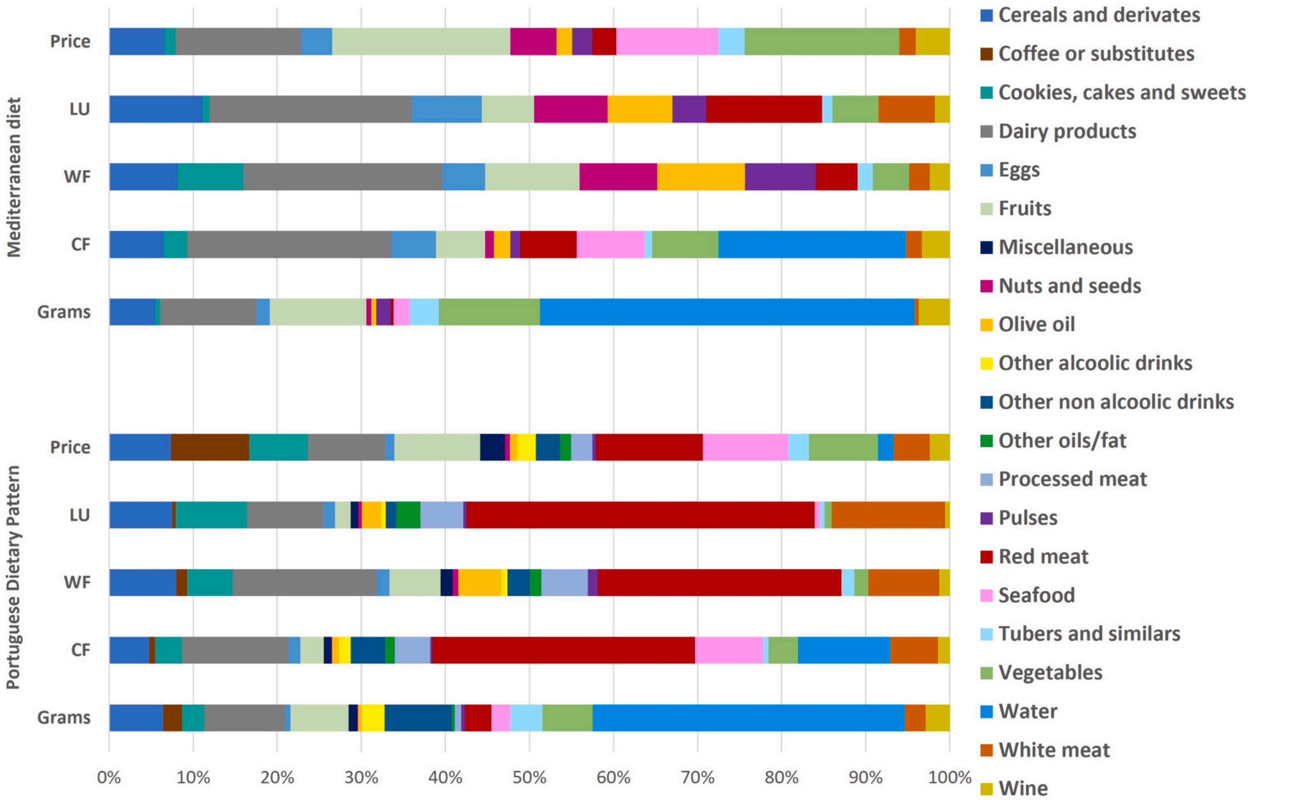


Fig. 3. Contribution of food groups to total dietary grams, carbon footprint, water footprint, land use, and diet cost for Mediterranean diet and Portuguese dietary pattern.

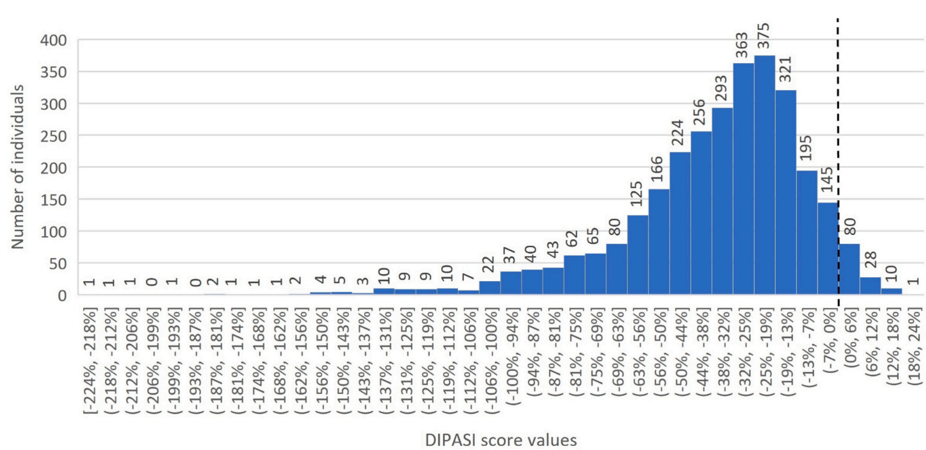


Fig. 4. Histogram of the DIPASI score. The vertical line present in the histograms represents the reference value of 0% of deviation from the reference diet.

4.3.1. *Dietary Pattern Sustainability Index (DIPASI) and nutritional quality, environmental impact, and diet cost*

When looking at the correlation between sub-scores (Fig. 9), we found no evidence of a strong correlation between dimensions, however the correlations are statistically significant. Environmental and nutritional sub-scores had a negative very weak correlation ($r_{spearman} = -0.04$, $p = 0.020$), nutritional and economic scores had a negative and weak correlation ($r_{spearman} = -0.28$, $p < 0.001$), and the environmental and economic scores presented a positive and moderate correlation ($r_{spearman} = 0.41$, $p < 0.001$).

Regarding DIPASI categories, the individuals classified within the high negative deviation category demonstrated larger environmental impact, poorer nutritional quality, and higher dietary costs compared to those falling under the no deviation or positive deviation categories (Table 2).

5. Discussion

The present paper introduces the DIPASI score, a novel method to evaluate the sustainability of dietary patterns by assessing multiple sustainability dimensions of dietary patterns and combining them in one single index. Some aspects bring the novelty of this composite indicator. Firstly, its holistic approach, as it not only evaluates nutritional quality but also incorporates considerations of environmental and economic aspects. Secondly, it uses the relative weights for the indicators within the environmental dimension, considering a proposal by the European Commission (Sala et al., 2017). Thirdly, it uses a reference diet, meaning that the DIPASI score is based on the comparison of specific dietary patterns with a reference diet. Fourthly, it uses indicators data for 1492 food items, allowing a more robust and detailed characterization of the

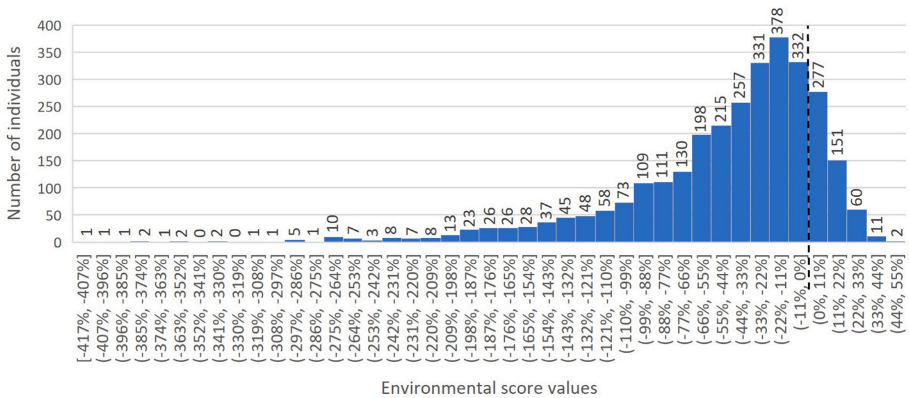


Fig. 5. Histogram of the Environmental sub-score. The vertical line present in the histograms represents the reference value of 0% of deviation from the reference diet.

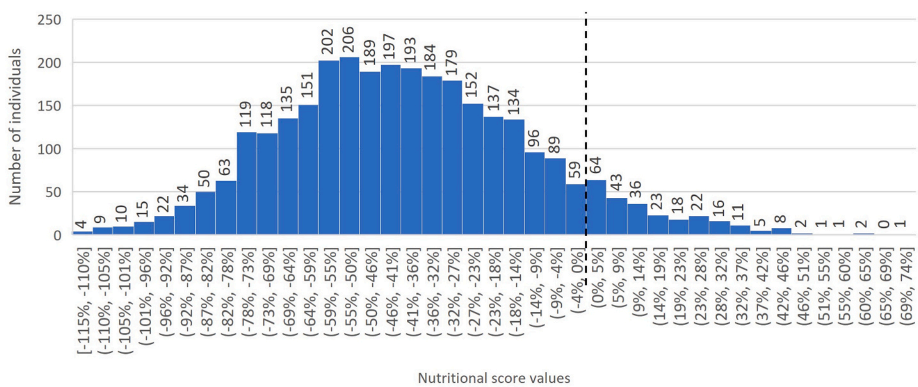


Fig. 6. Histogram of the Nutritional sub-score. The vertical line present in the histograms represents the reference value of 0% of deviation from the reference diet.

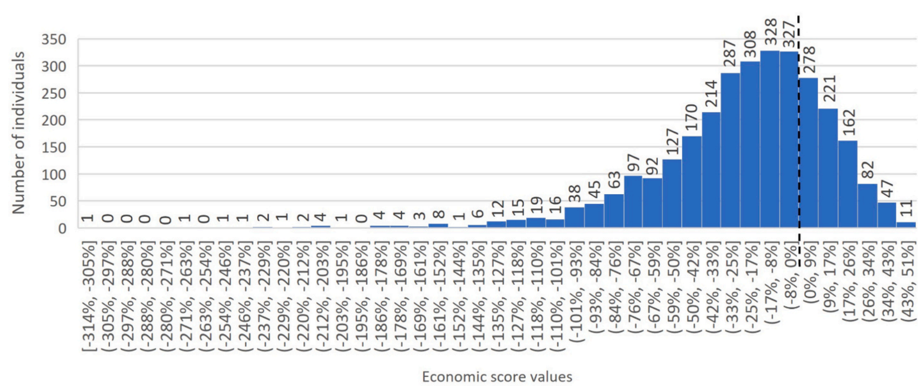


Fig. 7. Histogram of the Economic sub-score. The vertical line present in the histograms represents the reference value of 0% of deviation from the reference diet.

dietary pattern and leading to a long and complete database for each food item consumed by the case study population (i.e. Portuguese population). This index allows the assignment of an individual's diet sustainability score, where larger scores represent the most promising sustainability levels.

The DIPASI serves as a robust tool for policymakers and consumers, promoting sustainable dietary choices and informing effective policy interventions. By integrating environmental, nutritional, and economic dimensions, DIPASI provides comprehensive insights into the sustainability of dietary patterns, aiding in the development of guidelines aligned with sustainability goals. Policymakers can target specific food groups for intervention and promote dietary shifts aiming to reduce the overall environmental impact and improve public health. The index also allows for the monitoring and evaluation of policy effectiveness over time, ensuring that interventions remain effective and responsive to emerging challenges. For consumers, DIPASI can be used in educational campaigns to raise awareness about the sustainability of dietary choices. By providing clear information on the impacts of various diets, the index empowers consumers to make informed decisions that align with their health and sustainability goals. It also serves as a motivational tool, encouraging sustainable eating habits through personalized feedback and recommendations via digital platforms. In summary, DIPASI supports the development and evaluation of sustainable dietary policies while raising consumer awareness, fostering a healthier and more sustainable future.

The DIPASI exhibits some similarities with two recent and distinct

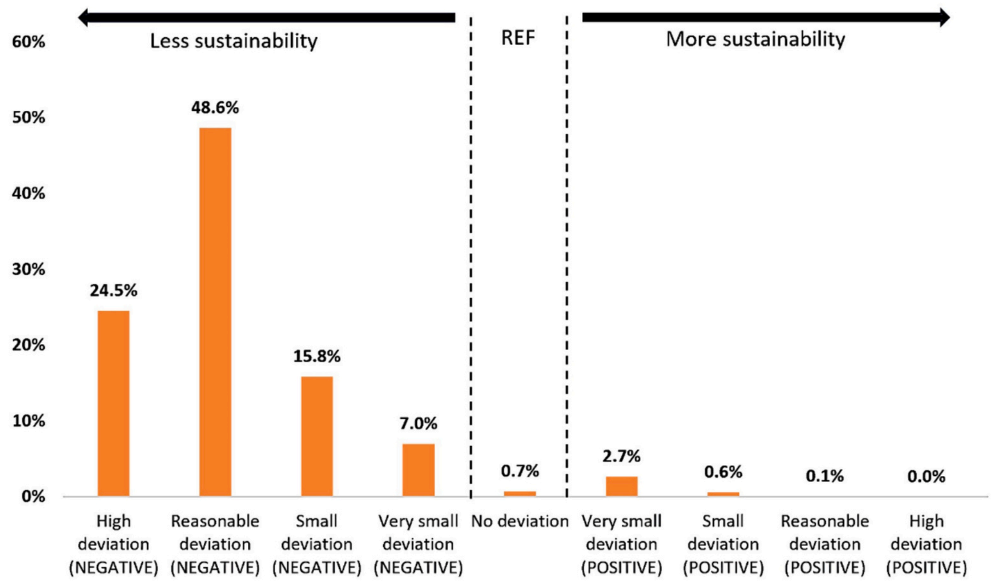


Fig. 8. Individuals' classification based on the results of DIPASI. The reference value considered is a deviation of 0%, obtained when the individuals equal the values of Mediterranean diet for each indicator. A positive deviation means a more sustainable diet, and in the contrary, negative deviation values means a less sustainable diet.

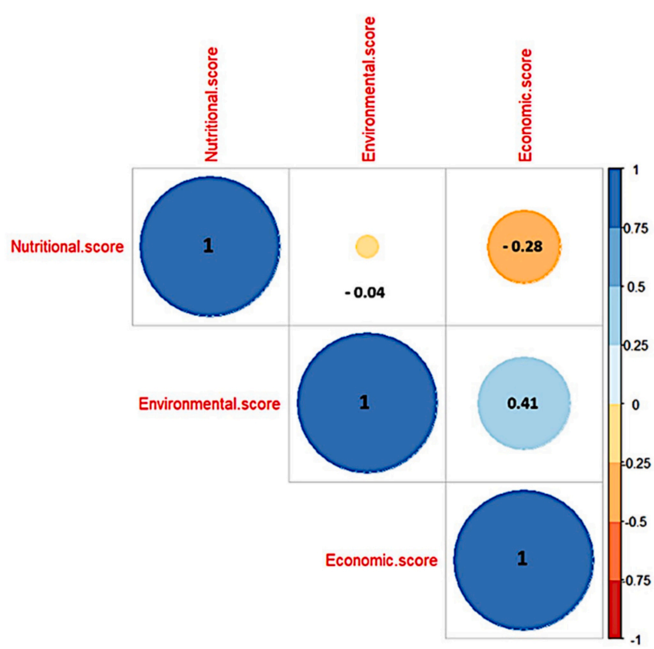


Fig. 9. Correlation coefficients between environmental, nutritional, and economic sub-scores.

indices in dietary assessment filed, namely the Sustainable Diet Indexes (SDI) developed by Seconda et al. (2019) and Fresán et al. (2020b). They all share a holistic perspective on dietary evaluation, equally weighing all the dimensions under consideration, and taking into account various relevant environmental aspects associated with the life cycle of food production processes. However, several differences may be found. One notable distinction pertains to the sociocultural dimension within the dietary assessment. In the case of DIPASI and SDI – developed by Fresán et al. (2020b), this sociocultural dimension is not incorporated, whereas Seconda et al. (2019) integrate this aspect into their index. Furthermore, our index, DIPASI, when calculating the environmental sub-score expressing all three environmental indicators makes use of relative weights for each one of the indicators (developed by JRC (Sala et al., 2017)). This feature is not taken into consideration in the calculation of the other indexes mentioned in the literature, where all environmental indicators used are given equal weights. While comparing the DIPASI results with those of other indices could potentially provide additional insights, such comparison is not feasible for several reasons. Significant methodological differences between the indicators, variations in the specific populations studied, and differing types of results presented in the literature make direct comparisons invalid and potentially misleading. Therefore, we have chosen to focus on thoroughly explaining and justifying our methodology and findings within the specific context of this study, which we believe provides accurate and meaningful insights.

In terms of the nutritional quality indicator, some authors adopted distinct indicators in their studies, differing from the one employed in our research. Fresán et al. (2020b) opted for the Dietary Guidelines Index for Americans 2015–2020, while Seconda et al. (2019) utilized a combination of indicators, including dietary energy balance, dietary energy density, dietary diversity index, and assessments of micronutrient deficiencies in vitamins and minerals as measures of nutritional quality. In our index, the NRD9.3 was selected because of its well-established utilization in the assessment of the nutritional quality and sustainability of diets (Batlle-Bayer et al., 2019; Castañé and Antón, 2017; Van Kernebeek et al., 2014).

The Portuguese Dietary Pattern has suffered significant transformations over the past decades (Bento et al., 2018). As described in the national statistical databases (INE, 2017), current Portuguese Dietary Pattern, are diverging from the traditional eating habits, based on MDiet (Rodrigues et al., 2022). Our results support that information. The sample presented a consumption below the MDiet reference for vegetables, fruits, dairies, cereals and derivates, tubers and similar, seafood, pulses, eggs, nuts, olive oil, wine, and water, and above for red meat, white meat, processed meat, other drinks, and cookies/cakes/sweets in line with the results obtained for environmental, nutritional, and economic indicators, where the Portuguese dietary pattern presented worse scores for the DIPASI sustainability index when compared to the MDiet.

Articles assessing the Portuguese population's adherence to the MDiet consistently show a low prevalence of individuals with high adherence, showing that Portugal has moved away from MDiet. For example, Mendonça et al. (2022) found low adherence in 8.8% of the population, moderate adherence in 62.5%, and high adherence in 8.7%.

Table 2
Comparison of environmental impact, nutritional quality, and dietary costs across DIPASI categories.

DIPASI categories	Carbon footprint (kg CO_2eq/day)	Water footprint (L/day)	Land use (m^2/day)	NRD9.3 (points)	Diet cost (euro/day)
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
High deviation (negative)	6.52 (2.43)	4399.01 (1590.37)	10.87 (5.27)	351.99 (231.68)	8.55 (2.77)
Reasonable deviation (negative)	4.12 (1.34)	2983.29 (969.24)	6.27 (2.46)	365.17 (245.80)	6.77 (1.99)
Small deviation (negative)	3.29 (0.97)	2551.93 (718.50)	5.04 (1.60)	411.74 (229.71)	5.65 (1.76)
Very small deviation (negative)	2.99 (0.85)	2343.12 (544.29)	4.41 (1.46)	486.28 (214.62)	5.26 (1.71)
No deviation	2.83 (0.67)	2372.60 (695.07)	3.92 (1.42)	556.51 (194.52)	5.31 (1.43)
Very small deviation (positive)	2.58 (0.99)	2176.46 (667.58)	3.88 (1.42)	526.90 (186.59)	4.53 (1.16)
Small deviation (positive)	2.60 (1.00)	2074.77 (671.55)	3.52 (2.18)	596.67 (291.03)	4.18 (1.77)
Reasonable deviation (positive)	2.09 (–)	1583.22 (–)	3.53 (–)	650.92 (–)	3.50 (–)

Legend: The median and interquartile range (IQR) values presented in the table were calculated for the environmental, nutritional, and economic indicators adjusted to a 2000 kcal intake. For categories with a very low number of individuals, the IQR could not be calculated.

Similarly, Andrade et al. (2020) reported that only 17.1% of their study population had high adherence to the MDiet, while most participants (62.7%) had moderate adherence, and 20.2% had low adherence. The lower adherence to the MDiet observed in these studies is consistent with our DIPASI results, which indicate significant deviations from the reference MDiet in terms of nutritional quality, environmental impact, and economic cost. In the literature, several articles evaluated the sustainability of MDiet and although the results are variable, the conclusions are consistent, namely that MDiet presents a more sustainable dietary model when compared to current consumption patterns in several countries (Annunziata et al., 2019; Batlle-Bayer et al., 2019; Belgacem et al., 2021; Benvenuti et al., 2016; Blackstone et al., 2018; Blas et al., 2019; Blas et al., 2016; Galli et al., 2017; Martinez et al., 2020; Naja et al., 2018; Rosi et al., 2020; Sáez-Almendros et al., 2013; Ulaszewska et al., 2017; Vanham et al., 2016; Vanham et al., 2021). In our study, MDiet presented an average of 3.30 kg CO2eq/day for CF, 2758.84 L/day for WF, 3.67 m2/day for LU, 5.71 euro/day for diet cost, and 668 for NRD9.3. These information aligns with the values per capita by other authors: CF between 0.9 and 6.88 kg CO_2/day, a WF between 600 and 5280 m3/day, and a diet cost between 3.33 and 14.42 euro/day (Bôto et al., 2022) As for the results obtained for the NRD9.3 score, our study is in line with the value obtained by Esteve-Llorens et al. (2020a, 2020b) for the MDiet scenario, 668 vs 635, respectively (González-García et al., 2018). These findings underscore the need for targeted interventions to promote the MDiet, leveraging its cultural significance and well-documented health benefits. With the recognition of its cultural relevance, various initiatives have been undertaken in Portugal to promote its adoption and preserve traditional dietary habits. For instance, educational campaigns have been launched emphasizing the health benefits of the MDiet and encouraging the consumption of locally sourced, and seasonal foods. Notable examples include the project iHERITAGE (ENI-CBCMED, 2024), the National Program for the Promotion of Healthy Eating of General Directorate of Health with a focus on the Mediterranean Diet (PNPAS, 2024), and *O Prato Certo* - Choose Your Plate Wisely (The Mediterranean Diet, 2024). This makes the use of the MDiet particularly relevant as the reference diet, allowing us to understand the extent of deviation in various sustainability dimensions and facilitating the monitoring of the evolution of the sustainability of Portuguese eating habits over time.

The WF of the Portuguese Dietary Pattern averaged 3162.88 L/day, which is lower than the 3570.3 L/day reported by (Gibin et al., 2022) for Portugal. Additionally, our study's WF aligns with the European average of 3227 L/day, as reported in a systematic review by (Harris et al., 2020) on the Water Footprint of Diets. For the CF, the Portuguese Dietary Pattern presented a mean value of 4.32 kg CO_2 eq/day, and for the NRD9.3 a value of 334. These values are in line with the study by Esteve-Llorens et al. (2020a), when evaluating the CF and nutritional quality of the Portuguese food balance, obtained the CF mean value of 4.30 kg CO_2eq/day and a NRD9.3 of 371, for the year of 2016. In a recent study conducted by Carvalho et al. (2023), the CF and the LU for the adult population (ages from 18 to 64) within the IAN-AF dataset were calculated, revealing a median values of 6.07 kg CO_2eq per day and 5.36 m^2/day, respectively (Carvalho et al., 2023). Notably, this exceeded the median CF obtained in our study, which stood at 3.76 kg CO_2eq per day, but is similar to our median LU values, 5.79 m^2/day. This divergence in results underscores a critical point: even when using the same data for food consumption patterns and indicators databases, significant variations may arise due to methodological differences resulting from the integration of environmental food footprints with food consumption data. For example, while Carvalho et al. (2023) employed the average impact value of hierarchical closest items for foods reported in IAN-AF 2015–2016 that are absent in environmental impact databases, our approach uses the highest value within the same subgroup for individual foods or, in the case of multi-ingredient products, the largest single footprint for overall ingredients. Other disparities often arise from the differences in the LCA compiled data used across databases, reflecting the inherent variability in food LCA data influenced by factors such as transportation methods, processing, retailing, consumption activities, packaging, and food preparation (Notarnicola et al., 2017). The study by Carvalho et al. (2023) exemplifies the sensitivity of dietary environmental impact assessments to methodological choices and data sources, underscoring the importance of transparent reporting and careful consideration of these factors in LCA-based research.

Upon analyzing the outcomes of DIPASI application to the Portuguese dietary habits, we observed that only 3.63% (n 109) of individuals exhibited no deviation or positive deviation relative to the reference diet suggesting that a majority of the population is making dietary choices that are notably less sustainable than the reference MDiet. Such options are resulting, potentially, in a higher environmental impact and diet cost but lower nutritional quality. This finding corroborates the existing literature, which has consistently indicated that the Portuguese population is gradually moving away from Mediterranean food traditions (Chen and Marques-Vidal, 2007; Rodrigues et al., 2008; Vilarnau et al., 2019). In terms of the sub-scores, the economic sub-score had the higher percentage of individuals above the reference (27.58%, n 827). This implies a lower dietary cost compared to the MDiet. This lower cost could be due to economic constraints and budget limitations, which often lead individuals to prioritize affordability over nutritional and environmental benefits, influencing dietary choices towards cheaper, less optimal nutrition and sustainability (Darmon and Drewnowski, 2015). The second-highest percentage of individuals surpassing the reference was associated with the environmental score, with 16.64% (n 499) having lower environmental impact than MDiet. This individuals could have diets even higher in plant-based foods and lower in animal products than MDiet leading to lower environmental impact, as these foods require fewer resources and produce fewer greenhouse gas emissions (Poore and Nemecek, 2018). The nutritional score performed less favorably, with only 8.50% (n 255) of individuals achieving nutritional quality levels superior to the MDiet. One possible explanation for this outcome is the selection of specific foods in the formulation of MDiet menus. The menus mainly included foods that go through minimal processing steps and provide the recommended portions suitable for a healthy diet. Consequently, certain items commonly found in the Portuguese Dietary Pattern, such as processed meats, coffee and its substitutes, non-wine alcoholic beverages, and non-alcoholic drinks other than water (e.g., fruit juices and soft drinks), are excluded. This finding suggests that adherence to the nutritional dimension of the MDiet, as encapsulated in DIPASI, remains relatively low within our sample. It also emphasizes the importance of a future analysis to understand the specific food choices and patterns that contribute to this deviation from the MDiet.

Overall, while our study contributes to provide valuable insights into the sustainability of dietary patterns, it is important to acknowledge few work limitations: a) Our study focuses on three widely recognized environmental indicators with widely accessible data – CF, WF, and LU, while we acknowledge the relevance of other environmental indicators such as acidification and eutrophication (Kameni Nematchoua, 2022). The focus is due to data availability, reliability, and comparability, which are the factors that primarily influenced our selection. The extensive food list analyzed posed challenges in obtaining comprehensive data for additional environmental impact categories. The inclusion of LU is also supported by data availability (Mertens et al., 2019) and relevance on agricultural sustainability (Kalisz et al., 2023). This is done although recognition the inherent uncertainty associated with LU assessment. In doing so, we expect that our methodological approach may provide the means for future incorporation of additional environmental indicators to provide a more comprehensive assessment of environmental impacts of dietary choices; b) there is inherent variability in the carbon and water footprints of food items due to differences in production practices, geographic locations, and other region-specific factors (Petersson et al., 2021). Certain assumptions were made to fill data gaps, such as using the highest value within a food subgroup when specific data were unavailable or using average values for different presentations of food products (e.g., fresh, frozen, dried). Also, the granularity of the data varies since not all food items had corresponding data for all impact categories, despite our use of detailed databases. The variability in environmental impact data, the methodological assumptions, and the data granularity, while part of the analysis, introduce a degree of uncertainty that must be acknowledged; c) another limitation relates to the lack of country-specific carbon footprints, which should be preferred to global ones, are not readily available for the whole set of food products consumed. The use of standardized data values from SU-EATABLE LIFE database helps to mitigate these variances and provide a more replicable assessment. However, undoubtfully future works may bring more specific data that may replace the data used to improve accuracy; d) the sociocultural dimension is not incorporated due to the lack of this data in IAN-AF 2015–2016 dataset (as e.g. seasonality, product origin, and ethical production). However, using the MDiet as the reference diet, given its cultural relevance in Portugal, could indirectly cover some social aspects of diet sustainability, specifically the cultural acceptance. e) the reference values obtained for MDiet reflect the specific foods used in the construction of the menus. For example, for fish, all items that were part of the menu have a value of zero in the LU indicator. The choice of other foods may affect the final reference value and the consequent comparison with other diets; f) Although the NRD9.3 score is a well-established tool for assessing the nutritional quality of diets, we recognize that this score does not encompass all essential nutrients, such as zinc and vitamin B12, which are crucial for overall health (Beal et al., 2023). These nutrients have been inversely associated to diets with lower environmental impact, meaning that in these diets the achievements of adequate intake of these nutrients tends to be more difficult. Generally, zinc and vitamin B12 are found in animal source foods, which are often limited in diets associated with lower environmental impact (Fresán et al., 2020a; Leonard et al., 2024); g) the method for estimating dietary costs based on retail prices assumes home consumption, potentially underestimating the variability of food costs, especially for foods consumed outside or self-produced. Furthermore, it is important to note that the prices of food components were collected in 2023, while IAN-AF questionnaires were obtained between 2015 and 2016. Consequently, any price and dietary changes that occurred during this seven-year interval are not factored into the analysis. This oversight could have meaningful implications, especially if specific food items experience price fluctuations at different rates compared to others, potentially influencing consumption patterns and dietary costs. Additionally, the economic assessment of the diet cost was based on retail prices from a single supermarket chain, which may not represent the full variability of food prices across different regions and retailers. Prices can be skewed by temporary promotions and discounts, and product availability varies between stores, leading to potential data inconsistencies. Additionally, the analysis did not account for seasonal variations in food prices. Seasonal products are available in greater quantities in various markets, which can lower their selling price, making seasonal products more economical compared to those produced out of season (André, 2013). It is then possible that not accounting for this may misrepresent true cost fluctuations; and finally, h) temporal differences in data collection are another limitation. The dietary data were collected from the National Survey on Food, Nutrition, and Physical Activity (IAN-AF) conducted from 2015 to 2016, while the environmental and economic data were gathered more recently. Changes in dietary habits, food production practices, and market prices over time are not reflected in this analysis, which could affect the comparability of the results.

6. Conclusion

The DIPASI score is a novel method designed to comprehensively assess multiple dimensions of dietary patterns—specifically, the environmental, nutritional, and economic dimensions—through a single index. The strength of the DIPASI lies in its methodological approach. A multi-criteria assessment of dietary sustainability and the use of a reference diet enables the assignment of an individual's dietary sustainability relative score. This score measures the percentage of deviation from an individual's diet in relation to a reference diet. The outcomes of the developed framework application will provide evidence to assist policymakers in making decisions aimed at achieving a more sustainable food system. Additionally, it will guide those responsible for formulating dietary guidelines towards promoting sustainable food consumption patterns and shaping better consumer choices. Furthermore, a comparative assessment of different dietary patterns will help identify pathways towards a more sustainable dietary pattern.

Results of the Portuguese case study highlighted a DIPASI median deviation of −31.27% (IQR 30.40%) from the MDiet (used as the reference diet). 73.1% (n 2195) of the individuals presented a reasonable to high deviation ($\leq -20\%$) in relation to the MDiet, indicating that the majority of the individuals show a higher environmental impact, poor nutritional quality, and higher diet cost compared with MDiet.

These outcomes raise questions about the factors contributing to the variations seen in the sustainability scores and emphasize the need for more detailed assessments. This will allow a better comprehension of the driving forces behind individual dietary choices. Further research work will be looking at it, aiming for a more comprehensive understanding of pathways towards a more sustainable food consumption pattern.

CRediT authorship contribution statement

Joana Margarida Bôto: Conceptualization, Formal analysis, Methodology, Writing – original draft, Visualization. **Belmira Neto:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Vera Miguéis:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Ada Rocha:** Conceptualization, Formal analysis, Methodology, Writing – review & editing.

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.spc.2024.07.029.

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