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Exploring the complexity of sustainable and healthy diets

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ABSTRACT

Amid escalating global concerns about environmental degradation and the pressing need to improve the nutritional quality of diets to meet the demands of a rapidly growing world population, the transformation of food systems has introduced social, economic, and environmental challenges. To address these issues, emergy synthesis, an accumulated energy measure considering environmental and anthropogenic transformation processes, offers a valuable scientific model for simulating and evaluating the environmental impacts of various dietary patterns. This approach facilitates the exploration of different scenarios, enabling the identification of sustainable solutions. The analysis provides comprehensive insights into diets that balance environmental sustainability and affordability by assessing resource use, environmental impacts, and economic costs associated with seven distinct dietary scenarios. The findings underscore that diets centered around meat consumption demand significantly higher energy inputs than plant-based diets and exceed established planetary thresholds for GHG emissions. This evidence highlights an urgent need to shift dietary patterns away from meat-centric diets to more effectively combat climate change. While the study found similar levels of agricultural land use across different diets, it revealed that plant-based diets significantly contribute to water consumption. These outcomes underscore the importance of making targeted and localized dietary adjustments to enhance the sustainability of food consumption. By minimizing the environmental load while simultaneously meeting the nutritional needs of an expanding population, these adjustments can play a crucial role in fostering a more sustainable interaction between human activities and the natural environment. The research findings have broader implications for improving human-environment interactions. They inform strategies for the various aspects of sustainable and healthy diets, focusing on their environmental support through emergy synthesis, which evaluates resource use, economic costs, and the associated environmental effects of different dietary patterns. In essence, this systematic approach to dietary planning, control, and monitoring is a pivotal measure in comprehensively and sustainably addressing environmental issues.

1. Introduction

Eating is fundamental to human existence, yet many face food insecurity due to hunger or lack of information, leading to poor-quality diets and nutrient deficiencies (Lenaerts and Demont, 2021). Simply distributing food is insufficient; a comprehensive approach integrating the entire production cycle is crucial for socially inclusive, environmentally sustainable, and economically viable development (Sachs, 2002). Evaluating dietary sustainability helps understand the complex social, political, economic, and

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environmental dynamics.

Over the past 50 years, global dietary habits have shifted towards foods detrimental to health and the environment (MacDiarmid et al., 2011). In developed nations, higher incomes have increased consumption of meat, dairy, oil, salt, and processed foods. Meanwhile, food system globalization has contributed to environmental degradation and biodiversity decline, reducing costs for nutrient-poor, energy-dense diets.

Food acquisition is crucial to achieving the Sustainable Development Goals (SDGs), including targets on hunger, nutrition, health, climate change, natural resources, biodiversity, and socio-economic activities (UN, 2015). Studies show that consumer interventions, such as vegan or vegetarian diets, can enhance health and mitigate climate change (Tilman et al., 2014; Scarborough et al., 2023). However, transitioning to these diets may cause deficiencies in the micronutrients typically sourced from animal products (Chen et al., 2019). Additionally, overconsumption undermines sustainability by exceeding individual needs and causing wastage (MacDiarmid et al., 2013; García et al., 2023). The current trend of high-energy, low-diversity diets supports agricultural intensification, challenging sustainability efforts.

Factors like population growth, intensified agriculture, evolving lifestyles, poverty, and food security underscore the necessity to redefine food systems, environmental, dietary norms, and health perspectives (Hallström et al., 2015; Lombardi et al., 2021). Scientists, stakeholders, and consumers must grasp the environmental, economic, social, cultural, and health dimensions integral to such diets (Fabri et al., 2021). Sustainable diets may have positive impacts, contributing to public health by diminishing diet-related chronic illnesses, aiding environmental conservation by reducing water and land usage and greenhouse gas emissions, and fostering economic sustainability through job creation and narrowing social gaps (Johnston et al., 2014; Carvalho et al., 2023).

Several studies have combined environmental metrics with various dietary change scenarios (Chen et al., 2019; Tilman et al., 2014; Scarborough et al., 2023), highlighting factors like socioeconomic status, lifestyles, and social context influencing food choices (MacDiarmid et al., 2012). However, most studies focus on single environmental aspects like greenhouse gas emissions. Methods like life cycle analysis (Calderón et al., 2010; Scarborough et al., 2023) primarily address environmental concerns and may neglect social and economic dimensions (Morgan, 2008). Thus, a diet with low greenhouse gas emissions might not be nutritionally sound, and a healthy diet could have high emissions (MacDiarmid et al., 2013).

In this pressing and complex context, where environmental degradation must be restrained within planetary boundaries (Steffen et al., 2015) and a nourishing diet ensured for a growing population, this study contrasts six proposed diets with Brazilian food consumption patterns using emergy synthesis. Emergy synthesis quantifies energy flows in an ecosystem, covering both natural and human processes. Combined with ecological modeling and simulations, it provides a robust framework for analyzing energetic relationships and efficiencies within ecosystems (Shah et al., 2019).

Assessing the provision of carbohydrates and proteins, the analysis juxtaposes environmental metrics (water consumption, agricultural land usage, and GHG emissions) against the cost associated with each diet, according to the following steps.

- to compare the environmental costs associated with the composition of different diets,
- discuss the impact of dietary choices on food affordability, socioeconomic inequalities, and nutrition, focusing on developing countries.
- To integrate emergy synthesis into ecological modeling to assess the extent of human influence on ecosystems by evaluating additional energy inputs from dietary choices and their impacts on natural energy flows.

This study aims to provide a foundational reference for future research, offering insights into the environmental and economic costs of different dietary choices. Ultimately, it seeks to inform policymaking and support decisions about sustainable dietary patterns and their implications.

2. Literature review

The SDGs envision countries eradicating hunger, ensuring food security, enhancing nutrition, and fostering sustainable agriculture by 2030 (UN, 2015). While diet modification strategies traditionally focus on health improvement and disease reduction, assessing their environmental impact is complex due to the diversity of foods and agricultural practices. Growing global populations and a shift towards resource-intensive diets associated with economic progress pose additional challenges (Ridoutt et al., 2017; Tilman et al., 2014). Empowering consumers to make informed decisions is crucial (Termote et al., 2013; de Grave et al., 2020). Kalt et al. (2021) conducted a sensitivity analysis exploring uncertainties in key parameters, revealing potential scenarios within a "biophysical option space" and providing insights into the interactions and future pathways of agricultural and environmental systems under various conditions.

The literature compares the environmental efficacy of various dietary patterns, integrating social, economic, environmental, nutritional, and health aspects (Chaudhary et al., 2018). Many studies apply environmental metrics to diet changes (Chen et al., 2019; Tilman et al., 2014). Torres et al. (2013) used a thermoeconomic approach to assess the environmental impact of food production stages, simulating shifts like moving from a meat-based to a vegetarian diet. Walker et al. (2021) created a repository to estimate the impacts of different food sourcing for dietary changes. Generally, transitioning to a sustainable diet involves reducing meat, moderately decreasing cereals, roots, and fish, and increasing vegetables, nuts, seeds, fruits, and legumes (Chen et al., 2019; Yanni et al., 2024). Springmann et al. (2017) concluded that addressing the food system's environmental impact requires combined actions, including dietary shifts to plant-based diets, technological advancements, and reduced food waste.

Most climate change studies focus on local or regional areas and advocate for reducing meat consumption. Auclair and Burgos

(2021) found that in America, diets with higher greenhouse gas emissions contained more animal-based foods, vegetables, fruits, and miscellaneous foods, while lower-emission diets had more cereals, grains, and bread. Heller et al. (2018) developed a food impacts database in the US to promote environmentally friendly consumer choices, identifying meat and dairy as the primary contributors to greenhouse gas emissions.

Similar findings emerged in Europe. Temme et al. (2015) showed that meat consumption significantly impacted greenhouse gas emissions in the Dutch population. Vinci et al. (2022) found that the Mediterranean diet had a carbon footprint lower than current food patterns in Italy. Gaillac and Marbach (2021) analyzed meat and dairy products, indicating that dairy-only diets are slightly less carbon-intensive. De Boer and Aiking (2021) evaluated the EU's Farm to Fork strategy, emphasizing its alignment with consumer concerns about global issues and its importance for policymakers, businesses, and consumers. The second environmental concern linked to dietary choices is land use, including deforestation, degradation, desertification, and biodiversity loss. Alexander et al. (2016) introduced the Human Appropriation of Food Land Index to assess diet impacts on farmland, finding that adopting the average Indian diet globally would require 55 % less farmland, while the average U.S. diet would need 178 % more. De Ruiter et al. (2014) correlated agricultural land use with dietary patterns in 16 European countries, highlighting significant land use differences due to variations in caloric food availability and national incomes.

Water use is another primary concern linked to dietary changes. Tom et al. (2016) examined water footprints when shifting from current diets to recommended ones. Blas et al. (2016) found that the American diet has a 29 % higher water footprint than the Mediterranean diet; switching to the latter could reduce daily water use in the U.S. by 30 %. Sáez-Almendros et al. (2013) noted that adopting the Mediterranean diet in Spain would significantly reduce greenhouse gas emissions (72 %), land use (58 %), and energy consumption (52 %), but water use only by 33 %. Zucchini et al. (2021) highlighted that omnivorous diets are the most water-intensive, with vegan and vegetarian diets reducing volumetric water footprints. Mirzaie-Nodoushan et al. (2020) proposed reducing water-intensive foods like red meat in Iran for water conservation and nutrition adequacy. Jalava et al. (2014) suggested that limiting animal protein intake could reduce water footprints by up to 15 % in regions like Latin America.

The energy approach is used for evaluating the environmental footprint of food production, allowing for detailed analysis based on unit energy values. Studies have applied this method to various categories, including grains (Ghaley et al., 2012, 2018), agro-ecosystems (Asgharipour et al., 2018; Almeida et al., 2020), animal protein (Østergård et al., 2015; Agostinho et al., 2019; Reis et al., 2021), and fish (Zhang et al., 2010). Broader studies have examined management strategies (Cristiano, 2021), production system performances (Agostinho et al., 2008; Giannetti et al., 2011; David et al., 2021), national agricultural systems (Jia and Zhen., 2021), and ecosystem services in food production (Giannetti et al., 2011; Shah et al., 2019). A comprehensive study on mango production highlighted the current agricultural model's reliance on chemical fertilizers, intensive labor, and minimal use of natural resources (Giannetti et al., 2016).

The most recent studies using energy to evaluate diets were published by Maassen et al. (2020), who investigated the environmental implications of diet choices in a "green" urban district in Sweden. Their study explored two hypothetical scenarios—a vegetarian and pescatarian diet—and found lower total energy flows for these scenarios compared to meat-inclusive diets. However, their findings suggested that specific dietary changes might not be the primary concern in addressing urban food consumption sustainability regardless of diet. Ghisellini et al. (2023) incorporated energy into a framework of indicators for monitoring the EU's Common Agricultural Policy to integrate indicators to assess efforts, monitor policy effectiveness, and support the circular economy model.

Despite recent research connecting environmental concerns to dietary choices, few studies have effectively combined environmental, nutritional, and economic indicators for valid comparisons. This field is still developing, lacking complete evidence to guide dietary interventions for reducing environmental impact. Most studies focus on local conditions or partial environmental aspects. Using energy synthesis to assess different food scenarios marks an innovative approach in this field that could help decision-making based on comprehensive and fair comparisons.

The literature review highlights the complexity of achieving sustainable and healthy diets, emphasizing the need for dietary shifts toward plant-based foods, such as vegetables, nuts, seeds, fruits, and legumes, to reduce environmental impacts like greenhouse gas emissions, land use, and water consumption. Meat and dairy are identified as major contributors to greenhouse gas emissions, while plant-based diets generally have a lower environmental footprint. Regional and cultural variations reveal the prevalence of high-emission diets in areas with greater consumption of animal-based products, highlighting the need for region-specific strategies. Additionally, the review underscores the importance of considering water and land use and calls attention to the economic and social dimensions, stressing consumer education and awareness as critical factors. However, significant gaps remain, including the need for more comprehensive assessments of multiple environmental factors, scalability analyses of costs, and exploration of long-term

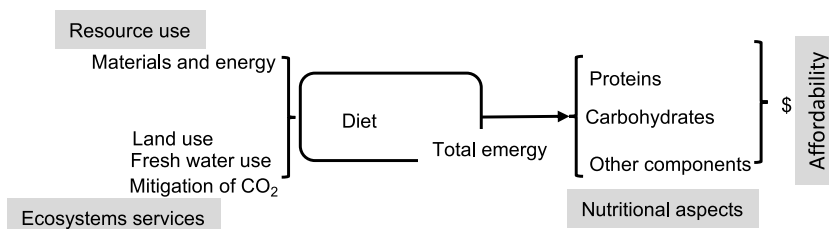


Fig. 1. Aspects explored for comparing energy between the diets.

environmental impacts, such as effects on biodiversity and resource management. This work, addressing some of these gaps, will enable the development of more effective global strategies for promoting sustainable and healthy diets.

3. Method

Fig. 1 illustrates the components involved in comparing emergy across various diets. This model incorporates key elements such as resource use, ecosystem services, nutritional aspects, and affordability. The left side of the figure shows materials, energy (comprising the total emergy), and the assessed ecosystem services. On the right side, the total emergy is segmented into proteins and carbohydrates (macronutrients), along with additional components encompassing total fats, micronutrients (such as vitamins and minerals), and fibers. These allocations align with daily reference values outlined in the Manual of Guidance to Food Industries (ANVISA, 2005). Finally, the emergy expended in acquiring the necessary monetary resources for food acquisition is considered in alignment with the ideal scenario of promoting health, affordability, and respecting and preserving the local environment.

3.1. Diets studied

The basis of data collection for Brazilian food acquisition, the BRA scenario, was the Household Budget Survey (IBGE, 2020), published by the Brazilian Institute of Geography and Statistics IBGE - POF 2017/2018 (Supplementary materials, Table S1). The values for food acquisition in Brazil (BRA) highlighted the considerable food insecurity documented by the Brazilian Research Network on Food and Nutrition Sovereignty and Security (FAO, 2021, 2022; Salles-Costa et al., 2022). As the primary objective involves comparing the environmental expenses associated with diet composition, the BRA scenario was aligned with the standards advocated by the World Health Organization (WHO, 2003). To achieve this, each component of the BRA diet was adjusted to match the total energy content in kcal of the Healthy Global Diet (HGD), based on adequate daily caloric intake for maintaining a healthy body weight.

Brazilian consumption consists of 323 food resources, which have been categorized into twelve food groups following the pattern of diets found in the literature: fruits, vegetables, legumes, seeds, cereal, meat, fish, eggs, milk, vegetable oils, tubercles, and other (Chen et al., 2019) to allow comparison (Table 1). Five additional dietary scenarios were considered: vegan (VGN), lacto-egg vegetarian (VGT), flexitarian (FLX), protein-oriented (PTO), and meat-oriented (MTO). These scenarios were calculated based on the ratio of their amounts in current and alternative diets available from Chen et al. (2019). The flexitarian diet includes small amounts of animal-sourced products, while the protein-oriented and meat-oriented diets contain higher amounts of eggs, dairy, or meat than the HGD diet. Alternative diets were balanced based on the composition of HGD.

It is worth noting that this work focuses on macronutrients by examining the emergy associated with protein and carbohydrate production. It highlights that vegan diets incur higher environmental costs for protein production, which is essential for those seeking to minimize their ecological footprint while ensuring adequate protein intake.

Processed foods were excluded from consideration since they account for only 3.89 % of the total mass. Individuals can create more satisfying and nutritionally balanced diets that enhance satiety, foster healthy eating habits, and support effective weight management by prioritizing mass over calories. This approach focuses on the quantity and quality of food, aiming for a healthier lifestyle. Moreover, many people prefer to emphasize mass when selecting diets based on satiety because foods high in mass, such as fruits, vegetables, and whole grains, take up more space in the stomach, promoting a feeling of fullness. Larger volumes of food, even when low in calories, signal to the brain that the stomach is full, helping manage appetite. Moreover, consuming larger portions increases meal satisfaction and reduces feelings of deprivation often accompanying calorie-restrictive diets.

Additionally, many high-mass foods, like fruits and vegetables, have significant water content, further contributing to a sense of fullness. Foods that are higher in mass and fiber typically lead to a slower and steadier rise in blood sugar levels, which can help manage hunger and prevent spikes and crashes that may lead to overeating (Slavin, 2005; Berkowitz, S. A., et al., 2014).

It is important to note that in Brazil, processed foods are often more affordable and readily available to the general population,

Table 1

Energy daily amounts of food distributed in twelve food groups for the diets evaluated (kcal/person day).

	Diets						
	BRA	HGD	VGN	VGT	FLX	PTO	MTO
Fruits	87.9	133.0	208.0	208.0	186.0	81.9	81.9
Vegetables	57.8	91.2	214.0	142.0	129.0	57.1	57.1
Legumes	96.7	14.7	247.0	67.6	47.0	14.7	0.0
Seeds	0.1	104.0	423.0	423.0	267.0	139.0	75.4
Cereal	354.0	660.0	634.0	634.0	634.0	634.0	634.0
Meat	299.0	102.0	0.0	0.0	66.4	326.0	434.0
Fish	14.7	11.3	0.0	0.0	8.2	15.5	15.5
Eggs	22.7	25.7	0.0	41.9	31.1	87.8	52.7
Milk	220.0	304.0	0.0	414.0	414.0	585.0	414.0
Vegetable Oils	303.0	468.0	639.0	639.0	639.0	639.0	639.0
Tubercles	41.0	120.0	230.0	230.0	230.0	230.0	230.0
Other	943.0	410.0	214.0	440.0	490.0	320.0	320.0
Σ	2440	2440	2810	3240	3140	3130	2950

making them a common dietary choice (Monteiro et al., 2017). Examples of these processed foods include canned vegetables, frozen meals, and processed meats, which offer convenience but can also result in less nutritious diets (Bernardi and Rinaldi, 2019). Additionally, many snack options, such as chips, granola bars, and trail mix, provide convenient choices for quick consumption. The prevalence and low cost of processed foods in Brazil present challenges, as they may encourage dietary patterns that favor convenience over nutritional value (Slater and Figueiredo, 2020). Given their dominance in the market, it is vital to recognize the public health implications of these foods and to seek strategies for promoting healthier choices that focus on whole, unprocessed foods while also considering accessibility and affordability for the population.

HGD (Global Healthy Diet, Springmann et al., 2016a), VGN (Vegan, Chen et al., 2019), VGT (Lacto Egg Vegetarian, Chen et al., 2019), FLX (Flexible Diet, Chen et al., 2019), PTO (Protein Orientation, Chen et al., 2019), MTO (Carnivorous Diet, Chen et al., 2019), BRA (adapted from Food Acquisition in Brazil, POF, 2017/2018). The study focuses on the main food groups for health impact estimates: red meat, fruits, vegetables, cereals, legumes, fish, eggs, milk, vegetable oil, tubercules, and seeds. Others refer to processed food, considering the main groups considered by TBCA (2020), Chen et al. (2019) and Springman et al. (2018).

The other five alternative diets are classified according to Chen et al. (2019).

- VGN, vegan diet, includes ample vegetable protein, mainly from cereals, legumes, fruits, and vegetables.
- VGT, lacto-egg vegetarian diet – allows the inclusion of products such as eggs and dairy products.
- FLX, flexitarian diet – involves small amounts of animal products.
- PTO, protein-oriented diet – includes regular amounts of animal protein with a balanced consumption between meat and dairy products.
- MTO, meat-oriented diet – includes substantial animal protein consumption,
- primarily from meat sources.

These dietary scenarios were carefully chosen to comprehensively analyze potential dietary shifts and their impacts on sustainability across multiple dimensions.

3.2. Energy synthesis

Energy accounts for both environmental and anthropogenic elements within transformation processes through a scientific model that interprets systems' operation through the interaction of various flows such as materials, energy, fuels, metals, and currency (Fig. 2). Consequently, the outcome offers a scientific measure of the accumulated energy required, either directly or indirectly, by each of these individual flows.

Fig. 2 illustrates the energy flow diagram for the seven diets examined. It encapsulates the common traits among all diet groups, primarily differing in the resource quantity generating each diet. The inputs originating from nature are depicted on the left side, while those supported by the economy are shown at the top. GHG emissions, soil erosion, and freshwater usage compose the flow of dispersed materials, recognizing that food choices, once consumed, disperse materials downstream.

Energy traces the resources utilized in producing a product or service back to their biospheric origin. It evaluates the environmental investment or support needed from the supplier or donor side, acknowledging the effort from natural ecosystems in generating

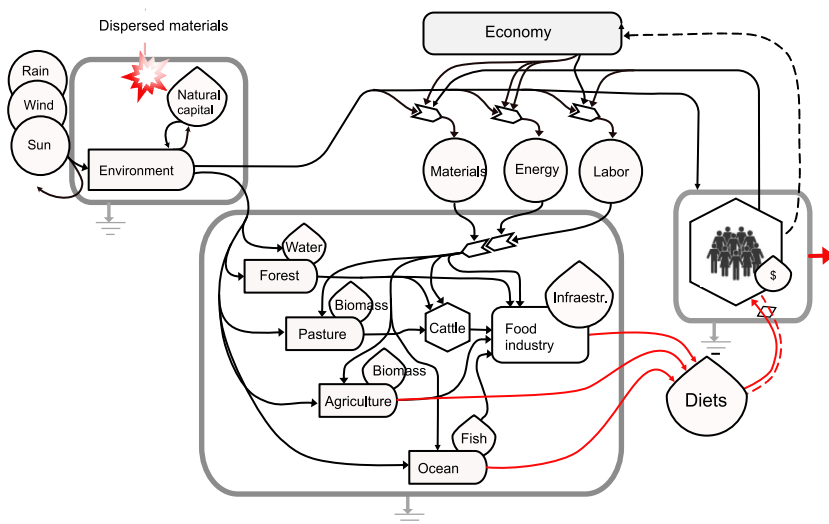


Fig. 2. Energy diagram representing the seven evaluated dietary systems. The red arrow represents the waste produced during production and consumption processes that, if not properly managed, is dispersed into the environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

raw materials and their utilization by humans. This method quantifies all necessary investments in solar energy joules (sej), allowing a direct comparison of biophysical and anthropogenic flows in consistent physical units, assessing any system performance by measuring resource use intensity from both natural and economic perspectives.

The energy daily amounts of food per component in each diet (kcal/person day) were multiplied by unit energy values (UEV, Supplementary Materials – Table S2) obtained from existing literature and adjusted to the global energy reference base of 12.1×10^{24} sej/year. This baseline refers to the overall energy supporting the biosphere, recalculated in 2016 after a thorough reassessment of energy contributions (Brown et al., 2016).

Calculating the energy needed for carbohydrates and proteins utilized the figures sourced from the Brazilian Table of Food Composition (TBCA, 2020). Refer to the complete table in the Supplementary Materials (Table S1) for comprehensive details.

The greenhouse gas emission conversion factors related to GHG emissions in agriculture, focusing on crops, cattle, fish, and sea-food, were extracted from Chen et al. (2019) and Tubiello et al. (2013) (Table 2). Data regarding cultivated land and freshwater use (both surface and groundwater) were sourced from the International Model for Policy Analysis of Agricultural Commodities and Trade (Robinson et al., 2015). The values presented reflect global average emissions, as specific data were unavailable in most cases. This approach may lead to either overestimating or underestimating the carbon emissions or land/water use associated with diets, depending on whether the production systems of specific food items consumed or recommended are more intensive or extensive than global averages. We also acknowledge that emissions can vary significantly based on region and production methods, and we believe future research should prioritize incorporating emissions data specific to the regions where the food is sourced.

Several studies have assessed the environmental impacts of individual foods or food groups primarily using the life cycle assessment approach (Poore and Nemecek, 2018). However, these studies are not directly comparable to the food-related planetary boundaries calculated by Springmann et al. (2017), which were used in our analysis due to their consistent modeling framework that allows for direct comparison of diet-related environmental impacts. Exceeding these planetary boundaries poses risks to the stability of the Earth's systems, ultimately jeopardizing human health. The recent EAT-Lancet Commission report on Healthy Diets from Sustainable Food Systems also employed these footprints and planetary boundary values to evaluate the environmental sustainability of diets across various scenarios (Willett et al., 2019).

Utilizing energy-based equations to evaluate GHG emissions, agricultural land use, and freshwater consumption is crucial for understanding dietary choices' implications. These equations highlight the ecosystem services required to support and manage these choices rather than merely quantifying the negative impacts of various diets. This shift in perspective promotes a more holistic discussion about sustainability and environmental responsibility within food systems, encouraging insights into enhancing ecological resilience while meeting human dietary needs (Walter and Moser, 2019).

To calculate the energy required to dilute the GHG emissions, Equation (1) quantifies the air needed to disperse each diet's emissions to the average atmospheric concentration (Giannetti et al., 2016). It uses standard wind speed values in Brazil (4 m/s) and considers the natural CO₂ concentration (367 ppm in 1999, IPCC, 2018). The resulting values are then multiplied by the wind's UEV (1.28×10^3 sej/J; Giannetti et al., 2019).

$$\text{Energy to mitigate GHG emissions} = (1 / 2 \times m / c_{\text{nat}} \times v) \times \text{UEV} \quad (1)$$

where m the mass of emitted CO_{2eq} per gram of diet (g/per person day); c_{nat} the natural concentration of CO₂ and v the wind speed (m/s).

To calculate the energy of agricultural land use (Eq. (2)), the mass topsoil loss is multiplied by the UEV of 1.30×10^5 sej/g (topsoil), and for computing the energy associated with freshwater use (Eq. (3)), the UEV of 2.56×10^5 sej/g (Giannetti et al., 2019).

$$\text{Energy of Agricultural Land use} = A \times k_1^{-1} \times \text{UEV} \quad (2)$$

$$\text{Energy of Fresh Water use} = C \times k_2^{-1} \times \text{UEV} \quad (3)$$

where A is the area of agricultural land (m²), C represents the daily freshwater consumption per person, k_1 (m²/g) and k_2 (m³/g) the conversion factors (Table 2).

Table 2

Conversion Factors related to Emission, Use of Agricultural Land and Consumption of Fresh Water to each resource (Chen et al., 2019, Tubiello).

	CO ₂ emission (kgCO _{2eq} /g)	Agricultural Land (m ² /g), k ₁	Use Water (m ³ /g), k ₂
Fruits	8.82E-02	1.01E-03	3.08E-04
Vegetables	6.32E-02	5.29E-04	9.19E-05
Legumes	2.28E-01	1.08E-02	9.24E-04
Seeds	6.91E-01	6.22E-03	4.19E-04
Cereal	2.90E-01	3.54E-03	5.01E-04
Meat	1.04E+01	5.73E-03	3.36E-04
Fish	1.30E-01	6.72E-04	4.52E-05
Eggs	1.55E+00	6.75E-03	4.33E-04
Milk	1.22E+00	1.34E-03	8.01E-05
Vegetable Oils	1.44E+00	7.06E-03	3.14E-04
Tubercles	1.08E-01	9.99E-04	4.14E-04
Other	2.16E-01	3.29E-03	3.51E-04

The emergy required to generate the money needed to purchase each diet was considered a proxy for affordability. Higher emergy consumption to acquire a diet implies fewer resources available for other purposes. An average price for each of the 323 items calculated, and thus, converting each diet's prices into emergy involves multiplying the current prices by Brazil's Emergy and Money Ratio (EMR), to simulate that all diets could be consumed in the country (see Table S3 in Supplementary Materials). The prices were retrieved from the Inter-Union Department of Socio-Economic Studies (DIEESE, 2023) for 2019. The EMR is determined by dividing the total emergy value of a country by its GDP in a given year, measuring the emergy invested to generate a unit of currency (Odum, 1996). For this study, the 2015 EMR was used, reflecting values of 2.81×10^{12} sej/US\$ for Brazil (NEAD, 2022).

4. Results

Fig. 3 illustrates the contrast in energy requirements (top) and emergy (bottom), highlighting the BRA and HGD diets. While BRA, MTO, and PTO scenarios show higher total energy, VGT and VGN show the lowest ones. The HGD and FLX scenarios, characterized by average environmental performance, require approximately 5.5×10^{12} sej to supply energy slightly beyond the 2000 kcal per person per day benchmark. The emergy needed to produce the Brazilian diet, while providing a similar caloric value as the Healthy Global Diet (HGD), heavily relies on meat, almost matching the PTO diet.

4.1. Nutritional aspects and ecosystems services

Proteins are essential for tissue building and repair, while carbohydrates provide energy. An analysis of daily carbohydrate and protein intake per individual for various diets reveals that the BRA, PTO, and MTO diets have the highest protein content, while other diets provide less than 100 g of protein daily. In contrast, the VGT, VGN, and FLX diets have the highest carbohydrate concentrations, with the BRA diet offering the least carbohydrates. Emergy analysis shows that producing one unit of protein demands significantly more emergy than carbohydrates across all diets (Fig. 4A). The BRA, PTO, and MTO diets require more environmental effort for carbohydrate supply, with fewer calories. The VGN diet requires approximately 20 % more emergy for protein production than other diets, reflecting a higher environmental cost.

While the potential micronutrient deficiencies linked to vegan and vegetarian diets is acknowledged, this work does not thoroughly investigate specific micronutrient profiles or dietary diversity, both essential for a comprehensive nutritional quality assessment and should be addressed in future studies. It is also important to note that although meat-based diets offer higher-quality energy, this does not necessarily lead to better health outcomes, highlighting the importance of achieving nutritional adequacy and environmental sustainability. Furthermore, the study does not examine the long-term health effects of chronic disease prevention or management.

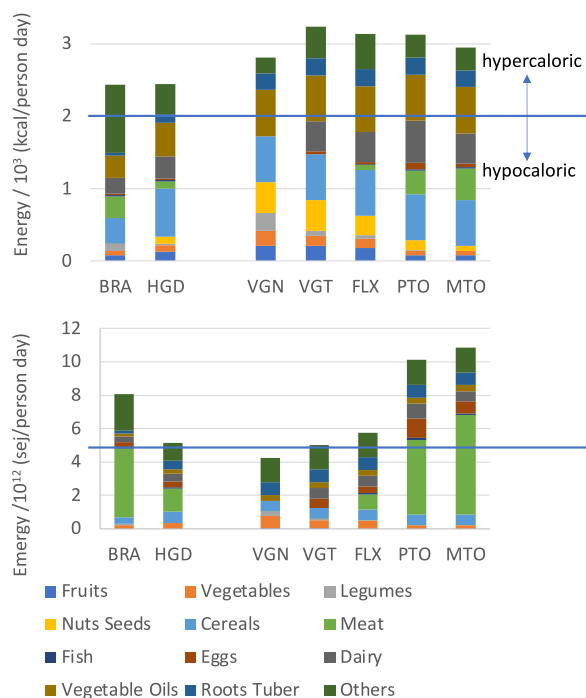


Fig. 3. Energy in kcal daily per person (top) and Emergy in daily sej per person (bottom) for each type of diet evaluated. Detailed values are provided in Supplementary Materials, Table S1 for energy and Table S4 for emergy values. Where: HGD (Global Healthy Diet, Springmann et al., 2016a), VGN (Vegan, Chen et al., 2019), VGT (Lacto Egg Vegetarian, Chen et al., 2019), FLX (Flexible Diet, Chen et al., 2019), PTO (Protein Orientation, Chen et al., 2019), MTO (Carnivorous Diet, Chen et al., 2019), BRA (Food Acquisition in Brazil, POF, 2017/2018).

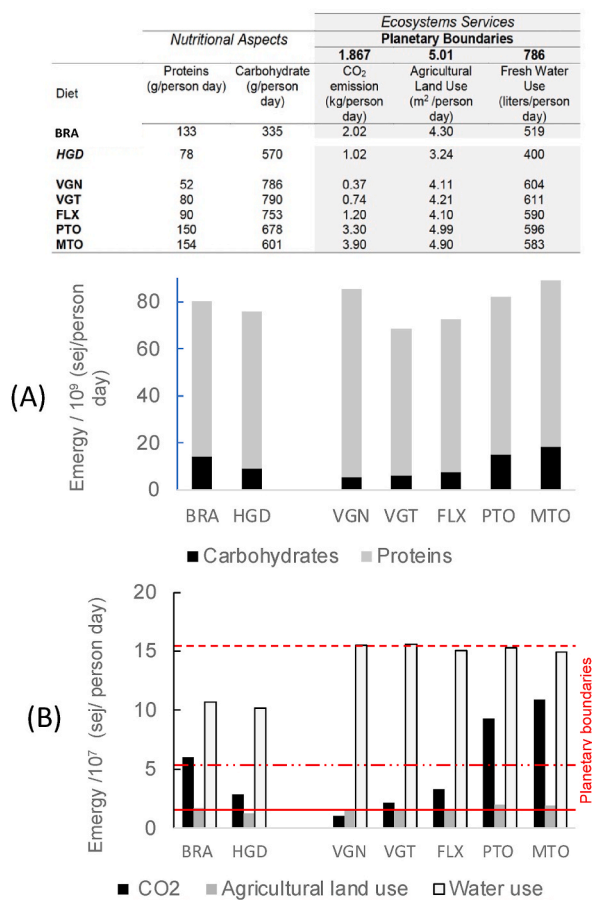


Fig. 4. Mass of carbohydrate and protein intake for each type of diet evaluated (TBCA,2020) and CO₂, Agricultural Land Use and the use of freshwater for each diet and the planetary limits (Springmann et al., 2017). (A) Required energy to supply carbohydrates and proteins for each diet and (B) Required energy to mitigate GHG emissions relative to agricultural land use and freshwater use for each diet. The red dashed lines correspond to the energy of the Planetary boundaries. Where: HGD (Global Healthy Diet, Springmann et al., 2016a), VGN (Vegan, Chen et al., 2019), VGT (Lacto Egg Vegetarian, Chen et al., 2019), FLX (Flexible Diet, Chen et al., 2019), PTO (Protein Orientation, Chen et al., 2019), MTO (Carnivorous Diet, Chen et al., 2019), BRA (Food Acquisition in Brazil, POF, 2017/2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Overall, while the paper establishes a foundational understanding of nutritional quality through energy synthesis, a more in-depth analysis of specific micronutrients and their long-term health implications would be beneficial.

The levels of GHG emissions, agricultural land use, and water consumption per person per day for each diet are shown in Fig. 4 (top), as well as the daily planetary limits per capita (Springmann et al., 2016b). The results indicate that the PTO, MTO, and BRA diets generate higher GHG emissions than the established planetary boundaries, confirming that these meat-oriented diets should be avoided from a climate change perspective (Auclair and Burgos, 2021; Heller et al., 2018). Except for the HGD diet, agricultural land use patterns tend to remain similar across all diets at the limit of the planetary boundary thresholds. The VGN and VGT diets exhibit the highest water consumption, especially due to fruit, vegetable, and cereal cultivation. In the VGN diet, these components comprise 56.2 % of its composition, whereas in the VGT diet, they constitute 44.2 % (TBCA, 2020).

Fig. 4B presents the emergy needed to offset carbon emissions and to accommodate land and water needs for each diet production. It is evident that both the BRA and HGD dietary patterns impose a relatively lower burden on the environment in terms of water use.

4.2. Incorporating the emergy investment associated with acquiring each diet

Fig. 5 illustrates the daily per capita economic costs for each diet acquisition in Brazil, expressed in emergy terms, along with a simulation depicting the transition to alternative diets. The PTO and MTO diets were omitted from consideration, as they would result in a further increase in meat consumption, which is already higher in the Brazilian diet compared to other options. Detailed values are available in Supplementary Materials, Table S4.

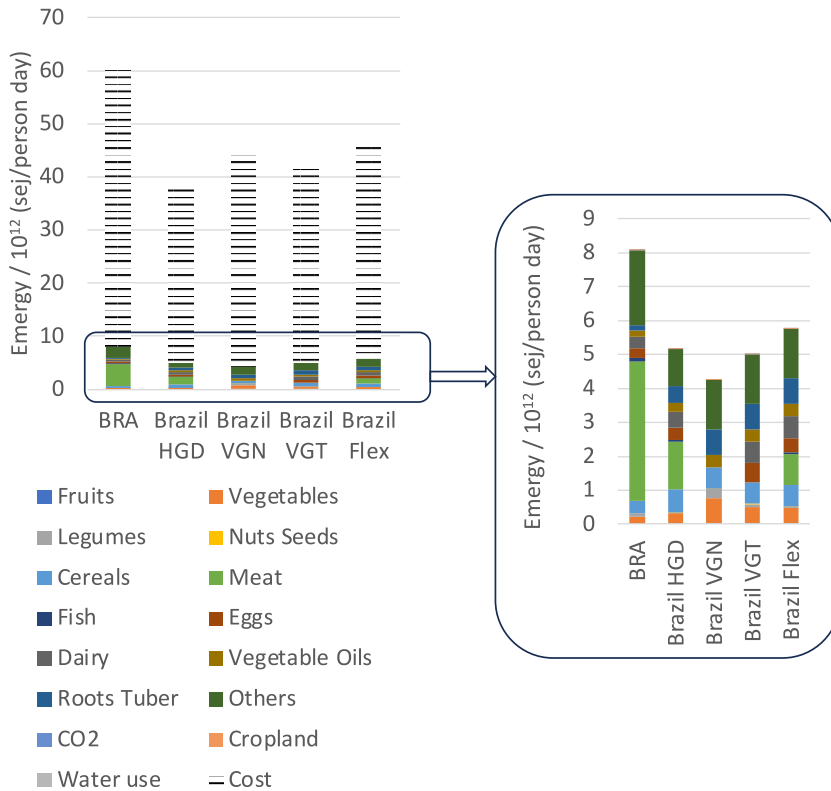


Fig. 5. Required energy to generate the currency to acquire each diet. Where: HGD (Global Healthy Diet, Springmann et al., 2016a), VGN (Vegan, Chen al., 2019), VGT (Lacto Egg Vegetarian, Chen al., 2019), FLX (Flexible Diet, Chen al., 2019), PTO (Protein Orientation, Chen al., 2019), MTO (Carnivorous Diet, Chen al., 2019), BRA (Food Acquisition in Brazil, IBGE, 2020; POF, 2017/2018), and BRA (Brazilian Diet). Detailed values are available in Supplementary Materials, Table S4.

5. Discussion

Odum (1996) introduced the concept of emergy to encapsulate the quality of incoming energy and resources, considering the environmental services that underpin a process and their interconnectedness across a chain of energy and matter transformations (see Fig. 2). While energy can generally be transformed into other forms, assuming full substitutability among all energy types across all scenarios is inaccurate. Understanding resource quality, energy quality, and energy concentration provides valuable insights into the trade-offs between dietary patterns in terms of nutritional benefits and environmental impacts. Resource quality refers to a resource’s ability to perform work or provide energy, linking it to food’s nutritional value and sustainability. Energy quality, derived from emergy theory, evaluates the form and versatility of energy, with meat-based diets often having higher energy quality due to their concentrated energy content. Similarly, energy concentration highlights the energy density in a resource, with meat-based diets providing efficient energy use but at greater environmental and social costs. While these qualities offer certain advantages, they also demand more resources, resulting in higher environmental impacts. Therefore, the importance of a balanced approach that considers both energy quality and sustainability in dietary recommendations is emphasized. In this regard, the application of emergy is well-supported by prior research on agrifood systems and food products, addressing various management strategies (Cristiano, 2021), production system performances (Agostinho et al., 2008; Giannetti et al., 2011; David et al., 2021), national agricultural systems (Jia and Zhen, 2021), and the ecosystem services involved in food production (Giannetti et al., 2011; Shah et al., 2019).

The emergy approach offers several advantages in this study, including a holistic evaluation of energy dynamics associated with various dietary patterns, which is essential for assessing sustainability. By integrating environmental services, it captures the quality of incoming energy and resources, illuminating the interconnectedness of energy and material transformations while providing a richer understanding of the environmental impacts of different diets. Emergy synthesis also allows for exploring various dietary scenarios identifying sustainable solutions by simulating their resource use, environmental impacts, and economic costs. This framework contrasts the energy embodied in each diet with the emergy required for its production, emphasizing sustainability and promoting dietary shifts in line with planetary boundaries. Overall, emergy synthesis integrates both natural and human processes, providing a comprehensive and robust framework for analyzing the energetic relationships within ecosystems and understanding how dietary choices affect natural systems, making it superior to other methods that may overlook these complexities.

Contrasting the energy embodied in each diet with the emergy required to obtain them (Fig. 3) clearly distinguishes the quality of energy flows crucial for composing each diet. According to emergy theory, quality corresponds to the form of energy and its

concentration. Higher quality aligns with a greater concentration of energy, providing enhanced flexibility (Ulgiati and Brown, 2009). Thus, despite the recommendations for adopting diets like veganism and vegetarianism to yield positive impacts on human health and mitigating climate change (Tilman et al., 2014; Scarborough et al., 2023), the results show that meat-based diets exhibit higher energy concentration - or higher energy quality - supplied to consumers, enabling them to drive various complexities in consumer systems.

Consumers who opt for meat-based diets access higher-quality energy, which could support more complex bodily functions and greater metabolic flexibility (Toujgani et al., 2023). However, this does not necessarily result in better health outcomes, as the overall nutritional profile and balance of a diet must also be considered. Research indicates that meat-based diets demand considerably more effort from both natural and human systems for their production (Springmann et al., 2017). This increased effort includes greater exploitation of natural resources, accelerated environmental degradation, and higher inputs of human labor and technological processes. Therefore, despite the potential benefits of higher-quality energy from meat-based diets, the increased energy requirement underscores significant environmental and social costs (Strässner and Wirth, 2024). These findings underscore the importance of a balanced approach to dietary recommendations, weighing the quality of energy available to consumers against the broader implications for sustainability and resource use.

The daily analysis of protein and carbohydrate supply offers critical insights for consumers. The VGN diet incurs a higher environmental cost for protein production, which is crucial for individuals seeking to reduce their ecological footprint while maintaining adequate protein intake (Yin et al., 2024). Diets such as BRA, PTO, and MTO provide higher protein content but also come with increased environmental costs per unit of protein. However, while energy analysis highlights the embodied energy required to produce one unit of protein and energy algebra—accounting for the energy memory involved in producing small quantities of protein without allocations—suggests higher energy consumption for vegan diets, this must be contextualized within the broader inefficiencies of animal agriculture. Animal-based protein production depends heavily on plant-based inputs, significantly increasing resource demands and creating a feedback loop where the higher energy cost of plant proteins indirectly exacerbates the inefficiency of animal agriculture. Ultimately, the issue revolves around system boundaries—holistic assessments that consider the entire lifecycle and resource allocation demonstrate that animal agriculture imposes greater environmental strain, reinforcing the sustainability advantage of plant-based diets when viewed through a comprehensive lens.

Carbohydrate-rich diets like VGT, VGN, and FLX have lower energy requirements for carbohydrate supply, suggesting a reduced environmental impact. Given these considerations, consumers aiming for a high-protein diet while being environmentally conscious should thoughtfully select protein sources that are both sustainable and nutritionally adequate. However, this choice can only occur if, from a broader perspective, it is supported by information provided by education and awareness campaigns and public policies. These public policies should consider, for example, agricultural practices, monoculture farming, biodiversity, and ecosystem services (Springmann et al., 2017; Jolliet, 2022).

Though planetary boundaries serve as a reference, BRA, PTO, and MTO diets exceed limits for GHG emissions, agricultural land use, and water consumption. This aligns with existing literature, which recommends reducing meat and vegetable oil intake, moderately decreasing cereals, roots, and fish consumption, and increasing vegetables, nuts, seeds, fruits, and legumes for a sustainable diet (Chen et al., 2019). It was also found that the BRA and HGD dietary patterns place a relatively lower environmental burden on water use. This contrasts with the findings of Zucchinelli et al. (2021), which relied solely on volumetric measures and did not consider resource quality. Their study indicated that the omnivorous diet had the highest water consumption and shifting to vegan and vegetarian diets reduced volumetric water footprints by approximately 10 %–14 %. However, when considering energy quality, all diets, except for BRA and HGD, exhibit comparable levels of water consumption.

The required energy for mitigating GHG emissions is significantly higher for meat-based diets, highlighting the complexity of environmental resource management. The BRA and HGD dietary patterns impose less strain on water resources, an advantage given global water shortages and the high-water demand of agriculture. However, the BRA diet produces higher GHG emissions, posing a severe climate risk. This tradeoff underscores the need to balance minimizing water use and GHG emissions, as addressing one environmental concern may exacerbate another. This juxtaposition emphasizes the need for a holistic and thoughtful approach to evaluating dietary and agricultural practices (Springmann et al., 2017), in which dietary changes should pay special attention to local contexts and environmental pressures, which will be a key challenge in defining region-specific pathways for the sustainable development of food systems. The goal is to find dietary patterns and agricultural systems that balance minimizing water use and GHG emissions. Achieving this may require changes in farming practices, innovative technologies, farmer education and training, and potentially shifting societal attitudes toward food and dietary preferences.

Finally, food affordability refers to having sufficient financial or physical resources to obtain or exchange adequate foods for a nutritious diet (Acheampong et al., 2022). The skewed energy-for-money exchange rate exacerbates socioeconomic inequalities, as wealthier individuals can afford diverse foods relatively easily, while disadvantaged populations often struggle to secure basic dietary needs, reinforcing existing inequities (Hwalla et al., 2016; Reis et al., 2021). Higher food costs negatively impact food security, leading to hunger and various forms of malnutrition. The economic strain of more costly diets often forces consumers to prioritize cheaper, less nutritious food options, adversely affecting their health. This issue is particularly critical in economically vulnerable countries, where access is a more significant challenge than availability (Nchanji and Lutomia, 2021).

The results revealed that the energy needed to generate the currency for the BRA diet exceeds the energy required to provide the diet itself. This situation echoes a common issue in developing nations (Dizon et al., 2019), where inhabitants often pay disproportionately more for a simple meal than those in wealthier countries (WFP, 2022). The energy values required to obtain the biophysical components of diets are consistently lower than those needed to afford them, suggesting that market prices might overestimate the actual value and that commercial transactions do not reflect a fair exchange of energy for money.

The results, particularly relevant in developing nations, reveal several consequences for consumers who experience higher relative

costs for simple meals, which can strain household budgets and hinder access to proper nutrition. This financial burden indicates the increased energy required to generate the currency needed for the BRA diet, underscoring existing economic inefficiencies, disparities, and expenses related to intermediaries and less efficient production processes (Salles-Costa et al., 2022). Transitioning to a Healthy Global Diet (HGD) or a flexitarian diet may help alleviate some of these economic and environmental pressures, potentially enhancing both affordability and access to nutritious foods. Future research should examine whether these findings apply across different geographical contexts, considering potential cultural resistance or preferences, political stability, market access, trade policies, and local food production capacities. A limitation of this study, similar to many in the literature, is its failure to account for the costs and logistics associated with transitioning to different diets, which may necessitate new infrastructure for production, distribution, and marketing. Additionally, future studies should address the potential environmental impacts as these diets scale up (Pérez-Escamilla et al., 2024), as well as the implications for biodiversity, agricultural practices, and resource management.

A key limitation of this study is its exclusive focus on sustainability indicators while excluding nutritional characteristics such as bioavailability and nutrient excretion, which could potentially influence environmental costs. These aspects were beyond the scope of the study's objectives, but acknowledging this omission is important. Future research could explore these factors to provide a more comprehensive understanding of the interplay between diet sustainability and nutritional outcomes.

6. Conclusions

Sustainable and healthy diets have become a key focus in research and policy discussions. Increasingly, efforts are being made to encourage consumers to align their food choices with dietary recommendations promoting health and environmental benefits. However, evaluating different diets regarding energy reveals intricate dynamics and complexities. This underscores the need for comprehensive assessments considering multiple environmental factors and resource utilization.

Acknowledging that the primary objective of diets is to provide health benefits to the population, a well-balanced diet with appropriate macro and micronutrient proportions is crucial for individuals' overall development and well-being. However, providing such diets adds complexity, necessitating different energy inputs to fulfill nutritional requirements. Meat-based diets demonstrate a higher energy demand but offer higher-quality energy. Conversely, plant-based diets require more energy for protein production than other diets. Vegetarian and vegan diets necessitate significant amounts of low-quality energy to meet nutritional needs, while meat-based diets also demand greater environmental efforts for carbohydrate production, and their presence in meat-based diets predominantly come from cereals and tubers, which are part of separate agricultural systems, their production indirectly contributes to the environmental impact of meat consumption.

The results indicate that determining the most sustainable diet is not straightforward. A sustainable diet is one that is designed to have a positive impact on both human health and the environment. It involves choices that minimize the depletion of natural resources, reduce greenhouse gas emissions, and promote biodiversity, while also considering social and economic factors. By understanding and implementing sustainable diets, one can effectively address food systems' interconnected social, political, economic, and environmental dynamics. This approach fosters a more harmonious relationship between human activities and the natural environment, ultimately contributing to long-term sustainability and resilience in food production and consumption. This work identified Healthy Global Diets (HDG), vegetarian (VGT), and vegan (VGN) diets as the most suitable for promoting sustainability and health due to their substantial environmental benefits, including lower greenhouse gas emissions, reduced land use, and decreased water consumption. While the conclusion emphasizes the environmental advantages of plant-based diets, the discussion highlights the practical benefits of flexitarian diets, which balance affordability, accessibility, and gradual meat reduction. The flexitarian diet, with occasional meat consumption, is noted for its flexibility and reduced environmental footprint compared to meat-heavy diets. Overall, the emphasis on reducing meat consumption aligns with the goal of combating climate change and environmental degradation, reflecting the complex interplay between economic factors, environmental impact, and sustainable dietary transitions.

Diets with minimal meat consumption consistently emerge as the most sustainable choices regarding resource use, ecosystem services, and cost. When selecting a sustainable diet, it is crucial to consider local factors such as resource availability, water supply, and agricultural land. Unfortunately, the Brazilian diet falls into an intermediate category, requiring more resources and ecosystem services than highly recommended diets such as HGD, VGT, and VGN. These options should ultimately depend on the region's resource and energy availability.

Despite any apparent contradictions that may arise from the tradeoff analysis results, they are consistent with numerous studies in the existing literature. These findings underscore the importance of considering local contexts and environmental pressures when making dietary changes. The intricate relationship between diet, environment, and costs necessitates a nuanced understanding of specific regional factors. Different regions have varying levels of resource availability, energy supply, and environmental constraints. Therefore, the optimal dietary choices for promoting individual health and environmental sustainability may differ by location.

Adhering to a universal set of dietary guidelines without considering local contexts can lead to suboptimal outcomes. Instead, a flexible approach that accounts for each region's unique circumstances is crucial. This approach allows for developing dietary recommendations that effectively balance health, environmental concerns, and local constraints.

CRediT authorship contribution statement

Cristiano A. Turim: Writing – original draft, Validation, Project administration, Methodology, Investigation. **Biagio F. Giannetti:** Validation, Supervision, Formal analysis. **Feni Agostinho:** Validation, Supervision, Methodology. **Cecilia M.V.B. Almeida:** Writing – review & editing, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cecilia Maria Villas Boas de Almeida reports financial support was provided by Paulista University. Cecilia Maria Villas Boas de Almeida reports a relationship with Paulista University that includes: employment. None If there are other authors, they 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.envdev.2025.101218>.

Data availability

Data was retrieved from open sources of the Brazilian government. The source address is indicated in the manuscript.

References

- Acheampong, P.P., Obeng, E.A., Opoku, M., Brobbey, L., Sakyiamah, B., 2022. Does food security exist among farm households? Evidence from Ghana. *Agric. Food Secur.* 11 (1), 24.
- Agostinho, F., Diniz, G., Siche, R., Ortega, E., 2008. The use of emergy assessment and the Geographical Information System in the diagnosis of small family farms in Brazil. *Ecol. Model.* 210, 37–57.
- Agostinho, F., Oliveira, M.W., Pulselli, F.M., Almeida, C.M.V.B., Giannetti, B.F., 2019. Emergy accounting as a support for a strategic planning towards a regional sustainable milk production. *Agric. Syst.* 176, 102647.
- Alexander, P., Brown, C., Arneith, A., Finnigan, J., Rounsevell, M.D.A., 2016. Human appropriation of land for food: the role of diet. *Glob Environ Change* 2016 41, 88–98.
- Almeida, C.M.V.B., Frugoli, A.D., Agostinho, F., Liu, G.Y., Giannetti, B.F., 2020. Integrating or Des-integrating agribusiness systems: outcomes of emergy evaluation. *Sci. Total Environ.* 729, 138733.
- ANVISA, 2005. *Mandatory Nutritional Labeling: Guidance Manual for the Food Industries - 2nd Version/National Health Surveillance Agency - University of Brasilia - Brasilia*, vol. 44p. Ministry of Health. ISBN 85-88233-17-7.
- Asgharipour, M.R., Hasan, Shahgholi H., Campbell, D.E., Khamari, I., Ghadiri, A., 2018. Comparison of the sustainability of bean production systems based on emergy and economic analyses. *Environ. Monit. Assess.* 191, 2, 2019.
- Auclair, O., Burgos, S.A., 2021. Carbon footprint of Canadian self-selected diets: comparing intake of foods, nutrients, and diet quality between low- and high-greenhouse gas emission diets. *J. Clean. Prod.* 316, 128245.
- Berkowitz, S.A., 2014. The association between dietary fiber intake and blood glucose levels in patients with type 2 diabetes. *Diabetes Care* 37 (6), 1587–1590.
- Bernardi, J.R., Rinaldi, A.E., 2019. Processed food consumption in Brazil: trends and implications for public health. *Cad. Saude Publica* 35 (8), e00119619.
- Blas, A., Garrido, A., Willaarts, B.A., 2016. Evaluating the water footprint of the Mediterranean and American diets. *Water* 2016 8, 448.
- Brown, M.T., Campbell, D.E., Vilbiss, C.D., Ulgiati, S., 2016. The geobiosphere emergy baseline: a synthesis. *Ecol. Model.* 2016 339, 92–95.
- Calderón, L.A., Iglesias, L., Laca, A., Herrero, M., Díaz, M., 2010. The utility of Life Cycle Assessment in the ready meal food industry. *Resour Conserv Recycl* 2010 54 (12), 1196–1207.
- Carvalho, C., Correia, D., Costa, S.A., Lopes, C., Torres, D., 2023. Assessing the environmental impact of diet – influence of using different databases of foods' environmental footprints. *J. Clean. Prod.* 416, 137973.
- Chaudhary, A., Marinangeli, C.P.F., Tremorin, D., Mathys, A., 2018. Nutritional combined greenhouse gas life cycle analysis for incorporating canadian yellow pea into cereal-based food products. *Nutrients* 10, 490.
- Chen, C., Chaudhary, A., Mathys, A., 2019. Dietary change scenarios and implications for environmental, nutrition, human health and economic dimensions of food sustainability. *Nutrients* 2019 11, 856.
- Cristiano, S., 2021. Organic vegetables from community-supported agriculture in Italy: emergy assessment and potential for sustainable, just, and resilient urban-rural local food production. *J. Clean. Prod.* 292, 126015.
- David, L.H., Pinho, S.M., Agostinho, F., Costa, L.J., Portella, M.C., Keesman, J.K., Garcia, F., 2021. Sustainability of urban aquaponics farms: an emergy point of view. *J. Clean. Prod.* 331, 129896.
- de Boer, J., Aiking, H., 2021. Climate change and species decline: distinct sources of European consumer concern supporting more sustainable diets. *Ecol. Econ.* 188, 107141.
- de Grave, R.B., Rust, N.A., Reynolds, C.J., Watson, A.W., Smeddinck, J.D., Monteiro, D.M.S., 2020. A catalogue of UK household datasets to monitor transitions to sustainable diets. *Global Food Secur.* 24, 100344.
- de Ruyter, H., Kastner, T., Nonhebel, S., 2014. European dietary patterns and their associated land use: variation between and within countries. *Food Policy* 2014 44, 158–166.
- DIEESE, 2023. *Inter-Union Department of Socio-Economic Studies (Departamento Intersindical de Estudos Sócio Economicos)*. <https://www.dieese.org.br/analisecectabasca>. December, 2023.
- Dizon, F., Herforth, A., Wang, Z., 2019. The cost of a nutritious diet in Afghanistan, Bangladesh, Pakistan, and Sri Lanka. *Global Food Secur.* 21, 38–51.
- Fabri, R.K., Martinelli, S.S., Perito, M.A., Cavalli, B., 2021. Absence of symbolic and sustainable aspects in recommendations for healthy eating: a qualitative analysis of food-based dietary guidelines. *Rev Nutr.* 2021 34, e200120.
- FAO, 2021. <https://www.fao.org/family-farming/detail/en/c/1153984/>. January, 2024.
- FAO, 2022. *The state of world fisheries and aquaculture 2022*. <https://www.fao.org/documents/card/en?details=cc0461en>. January, 2024.

- Gaillac, R., Marbach, S., 2021. The carbon footprint of meat and dairy proteins: a practical perspective to guide low carbon footprint dietary choices. *J. Clean. Prod.* 321, 128766.
- García, S., Bouzas, C., Mateos, D., Pastor, R., Álvarez, L., Rubín, M., Martínez- González, M.A., Salas-Salvadó, J., Corella, D., Goday, A., Martínez, J.A., Alonso-Gómez, A.M., Wärnberg, J., Vioque, J., Romaguera, D., Lopez-Miranda, J., Estruch, R., Tinahones, F.J., Lapetra, J., Serra-Majem, L., Riquelme-Gallego, B., Pintó, X., Gaforio, J.J., Matía, P., Vidal, J., Vázquez, C., Daimiel, L., Ros, E., Bes-Rastrollo, M., Guillem-Saiz, P., Nishi, S., Cabanes, R., Abete, I., Goicolea-Gómez, L., Gómez-Gracia, E., Signes-Pastor, A.J., Colom, A., García-Ríos, A., Castro-Barquero, S., Fernández-García, J.C., Santos-Lozano, J.M., Vázquez, Z., Sorlí, J.V., Pascual, M., Castaner, O., Zulet, M.A., Vaquero-Luna, J., Basterra- Gortari, F.J., Babio, N., Ciurana, R., Martín-Sánchez, M., Tur, J.A., 2023. Carbon dioxide (CO₂) emissions and adherence to Mediterranean diet in an adult population: the Mediterranean diet index as a pollution level index. *Environ. Health* 22 (1).
- Ghaley, B.B., Porter, J.R., Mentler, A., 2012. Emery synthesis of a combined food and energy production system compared to a conventional wheat (*Triticum aestivum*) production system. *Ecol. Indic.* 24 (2013), 534–542.
- Ghaley, B.B., Kehli, N., Mentler, A., 2018. Emery synthesis of conventional fodder maize (*Zea mays* L.) production in Denmark. *Ecol. Indic.* 87, 144–151.
- Ghisellini, P., Ncube, A., Rotolo, G., Vassillo, C., Kaiser, S., Passaro, R., Ulgiati, S., 2023. Evaluating environmental and energy performance indicators of food systems, within circular economy and “farm to Fork” frameworks. *Energies* 2023 16, 1671.
- Giannetti, B.F., Ogura, Y., Bonilla, S.H., Almeida, C.M.V.B., 2011. Accounting emery flows to determine the best production model of a coffee plantation. *Energy Policy* 39 (11), 7399e7407.
- Giannetti, B.F., Prevez, L., Agostinho, F., Almeida, C.M.V.B., 2016. Greening A Cuban local mango supply chain: sustainability options and management strategies. *Journal of Environmental Accounting and Management* 4 (3), 253–268, 2016.
- Giannetti, B.F., Almeida, C.M.V.A., Sevegnani, F., Agostinho, F., Garcia, R., Liu, G., 2019. Five sector sustainability model: a proposal for assessing the sustainability of production systems. *Ecol. Model.* 406, 98–108.
- Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. *J. Clean. Prod.* 91, 1–11.
- Heller, M.C., Willits-Smith, A., Meyer, R., Keoleian, G.A., Rose, D., 2018. *Environ. Res. Lett.* 13, 044004.
- Hwalla, N., El Labban, S., Bahn, R.A., 2016. Nutritional security is an integral component of food security. *Front. Life Sci.* 9 (3), 167–172. <https://doi.org/10.1080/21553769.2016.1209133>.
- IBGE, 2020. POF - consumer expenditure Survey. <https://www.ibge.gov.br/estatisticas/sociais/saude/24786-pesquisa-de-orcamentos-familiares-2.html>. September 2023.
- Jalava, M., Kumm, M., Porkka, M., Siebert, S., Varis, O., 2014. Diet change - a solution to reduce water use? *Environ. Res. Lett.* 9 (7), 074016.
- Jia, M., Zhen, L., 2021. Analysis of food production and consumption based on the emery method in Kazakhstan. *Foods* 10, 1520.
- Johnston, B.C., Kanters, S., Bandyrel, K., Wu, P., Najf, F., Siemieniuk, R.A., Ball, G.D., Busse, J.W., Thorlund, K., Guyatt, G., Jansen, J.P., Mills, E.J., 2014. Comparison of weight loss among named diet programs in overweight and obese adults: a meta-analysis. *JAMA* 312 (9), 923–933.
- Jolliet, O., 2022. Integrating dietary impacts in food life cycle assessment. *Front. Nutr.* 9, 898180.
- Kalt, G., Mayer, A., Haberl, H., Theurl, M.C., Erb, K.-H., 2021. Exploring the option space for land system futures at regional to global scales: the diagnostic agro-food, land use and greenhouse gas emission model BioBaM-GHG 2.0. *Ecol. Model.* 459, 109729.
- Lenaerts, B., Demont, M., 2021. The global burden of chronic and hidden hunger revisited: new panel data evidence spanning 1990–2017. *Global Food Secur.* 28, 100480.
- Lombardi, G.V., Parrini, S., Atzori, R., Gastaldi, M., Liu, G., 2021. Sustainable agriculture, food security and diet diversity. The case study of Tuscany, Italy. *Ecol. Model.* 458, 109702.
- Maassen, J.J., Rydberg, T., Bergquist, D., 2020. Emery synthesis of food preparation and diets in the “green” urban district rosendal, in uppsala, Sweden. *Journal of Environmental Accounting and Management* 8 (1), 55–71.
- MacDiarmid, J.I., 2013. Is a healthy diet an environmentally sustainable diet? *The Proc Nutr Soc* 2013 72 (1), 13–20.
- MacDiarmid, J.I., Kyle, J., Horgan, G., Loe, J., Fyfe, C., Johnstone, A., McNeill, G., 2011. Livewell: a Balance of Healthy and Sustainable Food Choices. World Wildlife Federation-UK, London. Project report.
- MacDiarmid, J.I., Kyle, J., Horgan, G.W., Loe, J., Fyfe, C., Johnstone, A., McNeill, G., 2012. Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? *Am. J. Clin. Nutr.* 96 (3), 632–639.
- Mirzaie-Nodoushan, F., Morid, S., Dehghanisani, H., 2020. Reducing water footprints through healthy and reasonable changes in diet and imported products. *Sustain. Prod. Consum.* 23, 30–41.
- Monteiro, C.A., Cannon, G., Levy, R.B., 2017. Ultra-processed foods: what they are and how to identify them. *Public Health Nutr.* 21 (1), 95–100.
- Morgan, K., 2008. Greening the realm: sustainable food chains and the public plate. *Reg. Stud.* 42 (9), 1237–1250.
- Nchanji, E.B., Lutomia, C.K., 2021. Regional impact of COVID-19 on the production and food security of common bean smallholder farmers in Sub-Saharan Africa: implications for SDG’s. *Global Food Secur.* 29, 100524.
- NEAD, 2022. National environmental accounting database V2.0. <http://www.emery-nead.com/country/data>. January 2022.
- Odum, H.T., 1996. Environmental Accounting. EMERGY and Environmental Decision Making. John Wiley & Sons, New York, 1996.
- Østergård, H., Wright, C., 2015. Renewability and emery footprint at different spatial scales for innovative food systems in Europe. *Ecol. Indic.* 62, 220–227, 2016.
- Pérez-Escamilla, R., Salles-Costa, R., Segall-Corrêa, A.M., 2024. Experience-based scales of food insecurity and food security governance: a case study from Brazil. *Global Food Secur.* 41, 100766.
- Poore, J., Nemecek, T., 2018. Reducing food’s environmental impacts through producers and consumers. *Science* 360, 987–992.
- IPCC, 2018. In: Prentice Lead, I.C., Farquhar, G.D., Fasham, M.J.R., Goulden, M.L., Heimann, M., Jaramillo, V.J., Khesghi, H.S., Le Quéré, C., Scholes, R.J., Wallace, D. W.R. (Eds.), *The Carbon Cycle and Atmospheric Carbon Dioxide*. <https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf>. December 2023.
- Reis, B.Q., Rojas Moreno, D.A., Nascimento, R.A., Luiz, V.T., Alves, L.K.S., Giannetti, B.F., Gameiro, A.H., 2021. Economic and environmental assessment using emery of sheep production in Brazil. *Sustainability* 2021 13, 11595.
- Ridoutt, B., Hendrie, G., Noakes, M., 2017. Dietary strategies to reduce environmental impact: a critical review of the evidence base. *Adv Nutr* 2017 8, 933–946.
- Robinson, S., Mason-D’Croz, D., Sulser, T., Islam, S., Robertson, R., Zhu, T., Gueneau, A., Pitois, G., Rosegrant, M.W., 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3. International Food Policy Research Institute (IFPRI), Washington, DC, USA, 2015.
- Sachs, I., 2002. Paths to Sustainable Development. Organization: Paula Yone Stroh, Rio de Janeiro: Garamond.
- Sáez-Almendros, S., Obrador, B., Bach-Faig, A., Serra-Majem, L., 2013. Environmental footprints of Mediterranean versus Western dietary patterns: beyond the health benefits of the Mediterranean diet. *Environmental Health: A Global Access Science Source* 12 (1), 118.
- Salles-Costa, R., Ferreira, A.A., Mattos, R., Reichenheim, M.E., Pérez-Escamilla, R., Bem-Lignani, J., Segall-Corrêa, A.M., 2022. National Trends and Disparities in Severe Food Insecurity in Brazil Between 2004 and 2018. *Current Developments in Nutrition* 6 (4), nzac034.
- Scarborough, P., Clark, M., Cobiac, L., Papier, K., Knuppel, A., Lynch, J., Harrington, R., Key, T., Springmann, M., 2023. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. *Nat Food* 4, 565–574.
- Shah, S.M., Liu, G., Yang, Q., Wang, X., Casazza, M., Giannetti, B.F., Agostinho, F., Lombardi, G.V., 2019. Emery-based valuation of agriculture ecosystem services and dis-services. *J. Clean. Prod.* 239, 118019.
- Slater, B., Figueiredo, R.M., 2020. Addressing the Public Health impact of ultra-processed food in Brazil. *Brazilian Journal of Epidemiology* 23, e200058.
- Slavin, J.L., 2005. Why whole grains are important. *J. Am. Diet. Assoc.* 105 (3), 495–503.
- Springmann, M., Godfray, H.C.J., Rayner, M., Scarborough, P., 2016a. Analysis and valuation of the health and climate change co-benefits of dietary change. *Proc. Natl. Acad. Sci. USA* 113, 4146–4151.
- Springmann, M., Mason-D’Croz, D., Robinson, S., Garnett, T., Godfray, H.C.J., Gollin, D., Rayner, M., Ballon, P., Scarborough, P., 2016b. Global and regional health effects of future food production under climate change: a modelling study. *Lancet* 387, 1937–1946.

- Springmann, M., Mason-D'Croz, D., Robinson, S., Wiebe, K., Godfray, H.C.J., Rayner, M., Scarborough, P., 2017. Mitigation potential and global health impacts from food emission pricing. *Nature Climate Changes* 7, 69–74.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., 2015. Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855.
- Strässner, A.-M., Wirth, W., 2024. Shades and shifts in flexitarian and meat-oriented consumer profiles in a German panel study. *Appetite* 197, 107298.
- TBCA, 2020. **Brazilian table of food composition**. <http://www.tbca.net.br>. August, 2020.
- Temme, E.H.M., Toxopeus, I.B., Kramer, G.F.H., Brokens, M.C.C., Drijvers, J.M.M., Tyszler, M., Ocké, M.C., 2015. Greenhouse gas emission of diets in The Netherlands and associations with food, energy and macronutrient intakes. *Public Health Nutr* 18, 2433–2445.
- Termote, C., Raneri, J., Deptford, A., Cogill, B., 2013. Assessing the potential of wild foods to reduce the cost of a nutritionally adequate diet: an example from eastern Baringo District, Kenya. *Food Nutr. Bull.* 35 (4), 458–479.
- Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. *Nature* 515, 518–522. <https://doi.org/10.1038/nature13959>.
- Tom, M.S., Fischbeck, P.S., Hendrickson, C.T., 2016. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. *Environ Syst Decis* 36, 92–103.
- Torres, C., Valero, A., Valero, A., 2013. Exergoecology as a tool for ecological modelling. The case of the US food production chain. *Ecol. Model.* 255, 21–28.
- Toujgani, H., Brunin, J., Perraud, E., Baudry, J., Kesse-Guyot, E., 2023. The nature of protein intake as a discriminating factor of diet sustainability: a multi-criteria approach. *Sci. Rep.* 13 (1), 17850.
- Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., Smith, P., 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ. Res. Lett.* 8, 015009.
- Ulgianti, S., Brown, M.T., 2009. Emergy and ecosystem complexity. *Communications in Nonlinear Science and Numerical Simulation* 14 (1), 310–321.
- UN, 2015. United Nations. Transforming Our World: the 2030 Agenda for Sustainable Development. United Nations, Report No. A/RES/70/1, New York, NY, USA.
- Vinci, G., Maddaloni, L., Prencipe, S.A., Ruggeri, M., Di Loreto, M.V., 2022. A comparison of the mediterranean diet and current food patterns in Italy: a life cycle thinking approach for a sustainable consumption. *Int. J. Environ. Res. Publ. Health* 19 (19), 12274.
- Walker, C., Pfister, S., Hellweg, S., 2021. Methodology and optimization tool for a personalized low environmental impact and healthful diet specific to country and season. *J. Ind. Ecol.* 25 (5), 1147–1160.
- Walter, J., Moser, W., 2019. Using emergy analysis to assess sustainability of food systems. *Renew. Sustain. Energy Rev.* 112, 349–358.
- WFP, 2022. **World food program**. <https://www.wfp.org/publications/wfp-annual-review-2022;wfp.org>. November, 2023.
- WHO, 2003. World health organization diet. In: Nutrition and the Prevention of Chronic Diseases: Report of a Joint WHO/FAO Expert Consultation, vol. 916. World Health Organization, Geneva, Switzerland.
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492.
- Yanni, A.E., Iakovidi, S., Vasilikopoulou, E., Karathanos, V.T., 2024. Legumes: a vehicle for transition to sustainability. *Nutrients* 16 (1), 98.
- Yin, J., Lin, J., Zhang, X., Wang, L., Liu, M., 2024. A balanced staple food structure effectively curbs the environmental impact and counters the nutrient losses from elevated CO₂. *Resour. Conserv. Recycl.* 205, 107545.
- Zhang, L.X., Ulgianti, S., Yang, Z.F., Chen, B., 2010. Emergy evaluation and economic analysis of three wetland fish farming systems in Nansi Lake area. *China J Environ Manage* 2010 Mar 92 (3), 683–694.
- Zucchinielli, M., Spinelli, R., Corrado, S., Lamastra, L., 2021. Evaluation of the influence on water consumption and water scarcity of different healthy diet scenarios. *J. Environ. Manag.* 291, 112687.