







## Integrating environmental, nutritional, and economic dimensions in Food choices: A case study on legume vs. meat-based burger patties

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### ABSTRACT

Addressing sustainability in modern food systems requires a multi-dimensional approach that considers environmental, nutritional, and economic aspects. This study applies Life Cycle Assessment (LCA) to analyze three burger patties (legume, chicken, and beef) across these dimensions, aiming to provide a holistic view of their impacts. While prior studies examined LCAs of plant-based meat and beef burgers with limited recipe data, this research expands on them by using commercial recipes for legume- and meat-based patties.

Conventional functional units, such as mass and individual nutritional content, fall short in capturing the full nutritional value. To bridge this gap, a modified Nutritional Rich Food Index (NRF Index) was introduced, integrating multiple nutrients (e.g., vitamins, minerals, macronutrients) into a single nutritional functional unit (n-FU) that better represents the overall nutritional quality.

Additionally, consumer purchase prices were incorporated to offer an economic perspective, and an economic functional unit (e-FU) was developed to assess the cost-effectiveness of each patty concerning their nutritional and environmental performance. This novel combination of functional units enables a more comprehensive evaluation, revealing trade-offs between sustainability dimensions.

**Results:** highlight significant environmental disparities among the products, with beef demonstrating the highest Global Warming Potential (GWP) at 4.64 kg CO<sub>2</sub> eq per 100 g, while the legume-based patty exhibited the lowest GWP at 0.113 kg CO<sub>2</sub> eq. Affordability indices indicate that meat options may be more accessible to budget-conscious consumers despite their higher environmental impacts.

This integrated assessment framework offers valuable insights for consumers and policymakers, supporting informed decisions that promote sustainable dietary choices aligned with nutritional and economic considerations.

### 1. Introduction

The growing awareness of the impact of food systems on ecosystems, resources, and health has prompted a reconsideration of our approaches to food production and consumption. A key research question is whether we can meet the food needs of the global population while staying within environmental limits, focusing on sustainable food systems. This concern has engaged various stakeholders in the pursuit of sustainable food systems [1,2]. Life Cycle Assessment (LCA) has emerged as a valuable tool for investigating the sustainability of products and processes within the food supply chain. In LCA studies, Functional Units (FUs) and Declared Units (DUs) are crucial for standardizing comparisons. A Functional Unit defines the service or function a product

provides, enabling meaningful comparisons across different products. In contrast, a Declared Unit specifies the exact quantity of a product being evaluated, often reflecting its actual output. Together, FUs and DUs ensure clear communication and consistency in assessing environmental impacts.

Traditionally, many food LCA studies have relied on conventional FUs based on mass or volume [3–5]. However, there is a growing advocacy for using nutritional functional units (n-FUs) that incorporate the nutritional value of foods into the assessment [6]. Utilizing n-FUs allows for a more nuanced evaluation of food products, as it considers diverse nutrient profiles and their contributions to health elements that standardized FUs often overlook.

The Food and Agriculture Organization (FAO) [7] emphasizes the

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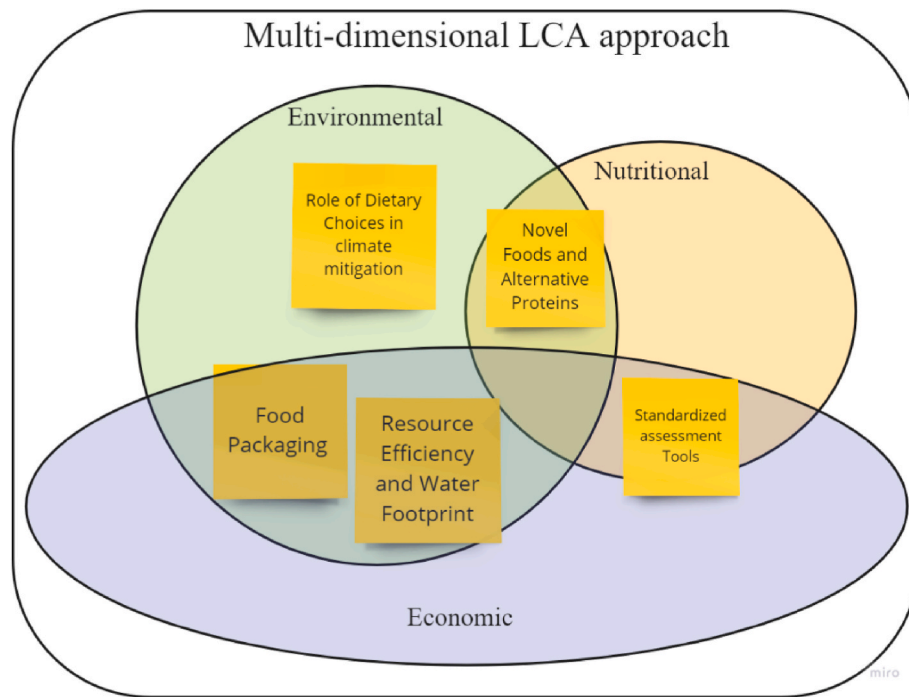
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**Fig. 1.** Key themes derived from the literature review on sustainability in food systems, encompassing environmental, nutritional, and economic dimensions.

need to address methodological challenges in LCA, including defining FUs related to nutrient amounts, energy content, and portion sizes. These considerations are vital for making informed decisions about food products. An appropriate definition of n-FUs is particularly important, as nutrient composition and individual dietary needs can vary significantly. Furthermore, food preparation methods can influence nutrient content, underscoring the need to account for these factors in LCA studies.

To contextualize this study and identify gaps in existing research, a literature review was conducted. Key thematic discussions were drawn from the findings to align with the scope of this study, providing insights into the environmental impacts of food systems and their broader sustainability implications (Fig. 1).

#### a. Role of dietary choices in climate mitigation

Several studies highlight the significant influence of dietary patterns on environmental sustainability. Research by Carlsson-Kanyama (1998) [8] and Hallström et al. (2015) [9] emphasizes the role of food choices in reducing greenhouse gas emissions and overall resource use. Detzel et al. (2022) [10] and Folwarczny et al. (2023) [11] further support this by demonstrating the lower environmental impact of plant-based diets compared to animal-based diets. The findings suggest that shifting towards plant-based eating can be a key strategy in mitigating climate change and promoting sustainable food systems.

#### b. Water and resource efficiency in food production

Water use in food production is another critical sustainability concern. Jolliet (2022) [12] discusses the water footprint of various diets, advocating for water-efficient food choices to minimize freshwater depletion. These findings align with broader discussions on sustainable food systems, where dietary shifts can reduce both carbon and water footprints.

#### c. Environmental impact of food packaging

Beyond dietary choices, packaging also plays a crucial role in the

environmental footprint of food systems. Kan & Miller (2022) [13] and Casson (2022) [14] examine the sustainability of food packaging materials and their impact on food preservation and waste reduction. Their insights highlight the need for sustainable packaging solutions to complement broader food system sustainability efforts.

#### d. Novel foods and alternative proteins

Emerging food technologies provide promising solutions for balancing nutrition with environmental sustainability. Mazac et al. (2023) [15] explore how novel foods, such as alternative proteins, contribute to both nutritional quality and reduced environmental impact. Their study suggests that integrating such foods into mainstream diets could support a transition towards more sustainable food systems.

#### e. Standardization and practicality of environmental impact assessments

To effectively implement sustainability measures in the food sector, accessible and standardized assessment tools are essential. Ahmad et al. (2019) [6] call for standardized LCA methodologies to ensure consistency in evaluating food products' environmental impact. Casson et al. (2023) [16] reinforce this need by advocating for simplified LCA tools that enable stakeholders to assess environmental impacts more efficiently.

The findings reveal that nutritional LCA aims to simultaneously integrate environmental impacts with nutrition and health aspects. However, defining the functions of food products is challenging, as they provide nutrients, satiety, pleasure, and cultural significance. While a single functional unit may not be feasible, metrics such as mass (g), energy (kcal or MJ), protein content remain widely recognized in nutrition education [17]. However, this approach often overlooks the complex relationship between foods and their nutritional benefits, potentially leading to excessive intake when individuals consume multiple products to meet a specific nutrient requirement (e.g., energy or protein), as these products may also contribute both positive and negative nutrients, disrupting balanced nutrition and leading to over-eating [18].

This study adopts a multi-dimensional approach, integrating environmental, nutritional, and economic assessments to evaluate legume- and meat-based burger patties. By combining these three dimensions, the research provides a more comprehensive view of food sustainability. In response to the challenges discussed earlier, a modified Nutritional Rich Food Index (NRF Index) was developed as a nutritionally normalized functional unit (FU) in this study. This index consolidates essential nutrients such as protein, fiber, vitamins, and minerals into a single score, balancing nutrients to encourage with those to limit, thus providing a comprehensive reflection of the patties' nutritional quality. This approach allows for a more balanced and realistic comparison of nutritional and environmental impacts.

Building upon the growing body of research on the environmental impact of plant-based meat alternatives [19], this study aims to further explore the sustainability and nutritional performance of food products utilizing various n-FUs. While Tang et al., 2024 [19] focused on the life cycle assessment (LCA) of plant-based meat analogues (PBMA) and traditional beef burgers, addressing gaps in publicly available PBMA recipes, our research extends this work by assessing legume-based and meat-based burger patties using commercial recipes. By comparing the environmental and nutritional performance of legume-based patties to meat alternatives, this study contributes to a more comprehensive understanding of plant-based food products within the broader context of sustainable food systems.

The economic functional unit (e-FU) is a metric introduced to integrate economic considerations into LCA by assessing the cost-effectiveness of food products alongside their environmental and nutritional performance. This approach aided consumers and policy-makers evaluate affordability [20] and sustainability of different products [21], addressing a critical gap in current LCA methodologies, which often overlook the interplay between environmental, nutritional, and economic factors. By incorporating e-FU, this study extends beyond conventional LCA approaches to analyze cost-benefit trade-offs in food choices. Additionally, the NRF Index serves as a nutritionally normalized functional unit (n-FU), bridging gaps in existing assessments that fail to capture the full nutritional value of foods. By leveraging commercial recipes for legume- and meat-based burger patties, this study enhances the real-world applicability of sustainability evaluations. This holistic approach enables a more balanced comparison of affordability, sustainability, and nutritional quality, providing valuable insights for informed decision-making.

## 2. Methods

According to the scope of the study, the environmental analysis of three burger patties was carried out using the LCA methodology and following the ISO 14040 and 14044 standards [22,23]. The LCA was applied to all levels of the production chain of two traditional meat and legume-based burger patties, considering: (1) cultivation/farming activities, (2) transformation of intermediate products, (3) final product processes, and (4) home consumption.

### 2.1. Goal and scope definition

#### 2.1.1. Declared unit and functional units

This study aims to assess the sustainability of legume- and meat-based burger patties by integrating environmental, nutritional, and economic dimensions using Life Cycle Assessment (LCA). To achieve this, different approaches were employed to define the declared unit (DU), nutritional functional units (n-FU), and economic functional unit (e-FU) based on energy content, key nutritional parameters, and cost-effectiveness to the products. This approach ensures that the study captures variations in both the quantity and quality of nutrients provided by different products while also considering their affordability. As discussed in the literature review section, DU (mass-based unit) is simple and easy to understand, but it doesn't consider food functionality or

**Table 1**  
Nutrient recommended intake values [25].

Recommended intake value	per meal/person	
Protein	18.48	g
Dietary fiber	10.00	g
Saturated fatty acid	5.20	in gram, as low as possible
Monounsaturated fatty acid	17.60	moderate
Polyunsaturated fatty acid	8.80	moderate
Cholesterol	120.00	mg
Carbohydrates	52.00	in g, (50 % E; 0.129 g/k.calorie)
Simple sugars	12.48	in g, (12 % E; 0.129 g/k.calorie)

nutritional value. Nevertheless, it serves as useful reference point for comparing relative results with the other FUs. Therefore, in this study, the DU is defined as the mass of a burger patty (100 g) was chosen as the basis for comparison since the primary data sources provided the composition of burger patties per 100 g, ensuring consistency in evaluation.

In the case of nutritional functional units, n-FUs, energy (expressed in kcal) is defined in this study as the amount of a burger patty providing 100 kcal of energy aligning with standard nutritional labels found on commercial food products.

When considering macro- and micronutrients, such as protein, fibre, fatty acids, cholesterol, and carbohydrates were assessed per 1 g, as higher reference values (e.g., 10 g or 100 g) would have made comparisons impractical due to the low absolute content of these nutrients in the patties and this ensured a more standardized and comparable assessment of burger patties.

To quantify the overall nutritional quality of each burger patty, a NRF index was developed as a functional unit to quantify the overall nutritional quality of each burger patty. The NRF Index integrates multiple essential nutrients into a single score by balancing nutrients to encourage (e.g., protein, fiber, vitamins, minerals such as iron) with nutrients to limit (e.g., added sugar, sodium, saturated fats, cholesterol, carbohydrates). Finally, the last n-FU proposed in this study was defined as 1 NRF index based on all nutrients contained in the food making it a suitable reference for comparing overall nutritional quality. The NRF index value of a product is calculated as follows:

$$NRF\ Index = \sum (NE_i/RIV_i) - \sum (NL_i/RIV_i),$$

NE (nutrients to encourage): Protein; fibre; vitamins A, C, and E; calcium; iron; magnesium, and potassium.

NL (nutrients to limit): carbohydrates, cholesterol, saturated fat; sodium; and added sugars.

RIV: recommended intake value, refer Table 1.

The study focused on adults with an average weight of 70 kg, a widely accepted reference weight in nutritional and toxicological studies. This standardization aligns with dietary guidelines established by the European Food Safety Authority (EFSA) [24]. Furthermore, it is assumed that approximately 40 % of their daily energy intake comes from a single meal, with lunch or dinner typically constituting the largest portion of daily calorie consumption. This assumption also reflects the typical energy proportion derived from a main meal, allowing the study to focus on a realistic scenario. Restricting the analysis to this proportion helps standardize the comparison of the nutritional content of the legume, chicken, and beef burger patties.

Similarly, the economic functional unit (e-FU) was introduced to evaluate the cost-effectiveness of the products, strictly within the context of the Italian region. The e-FU based on price per 100 g, reflecting the common commercial practice of selling food products by weight. Secondly, price per 100 kcal was incorporated to align with nutritional labels that often report price per energy content. Finally price per 1 NRF index was introduced as it offers a holistic assessment, integrating both cost and overall nutritional quality.

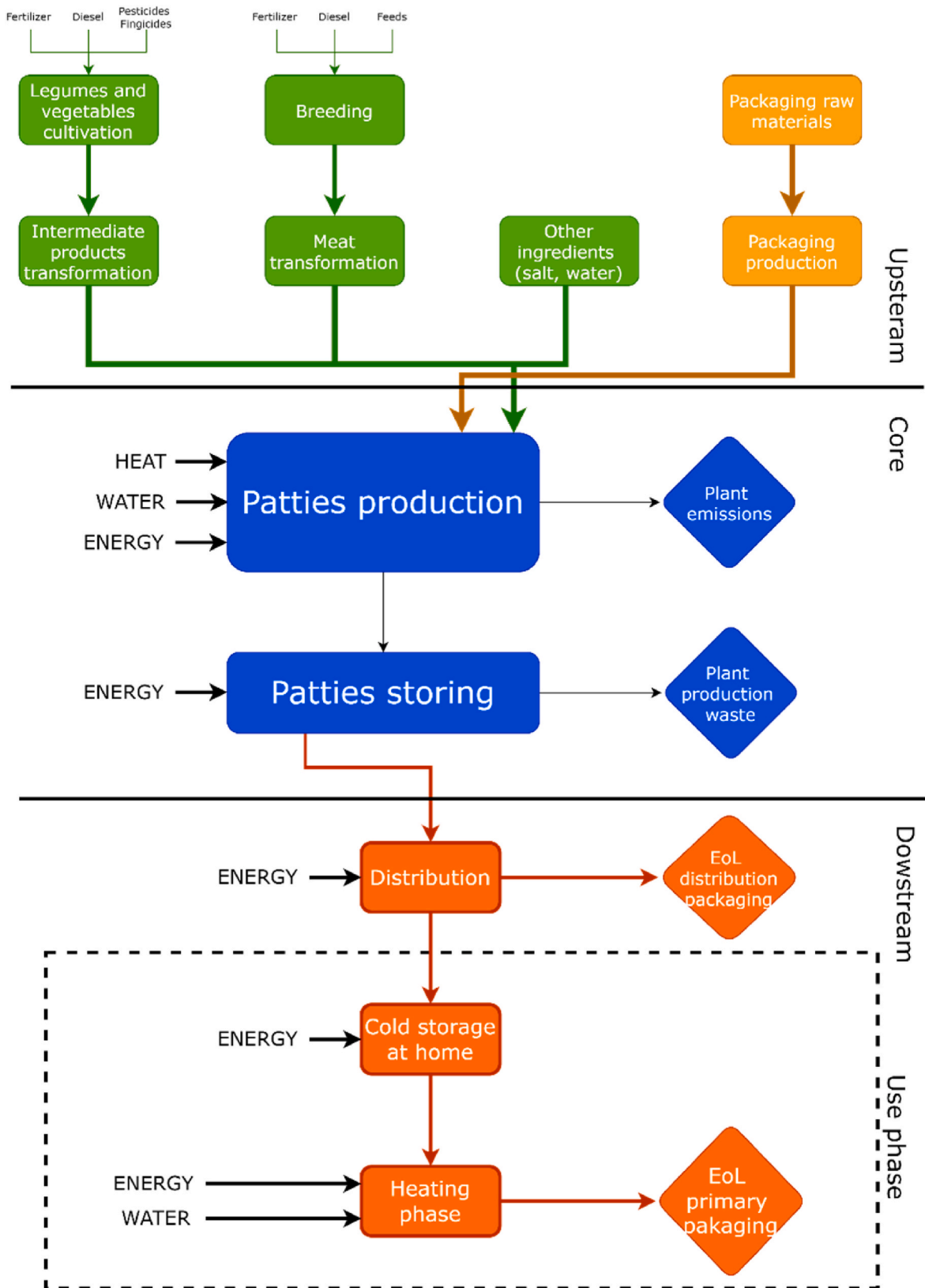


Fig. 2. System boundary definition.

This approach ensured that the functional units were standardized, allowing for a balanced comparison across the environmental, nutritional, and economic dimensions of food sustainability.

### 2.1.2. System boundaries

For all burger patties, this includes the production of the raw materials (cultivation/farming activities) and the production processes of the burger patties. Considerations related to the nutritional FU led to the

**Table 2**  
Composition of the three burger patties analysed.

Ingredients	Legume-based burger patty (g/100 g)	Beef-based burger patty (g/100 g)	Chicken-based burger patty (g/100 g)
Chickpeas	14.20	/	/
Barley	12.50	/	/
Spinach	3.50	/	/
Olive oil	1.00	/	/
White egg	3.00	/	/
Cheese	2.00	/	16.00
Process water	59.00	/	/
Beef meat	/	98.00	/
Salt	/	2.00	2.00
Chicken meat	/	/	82.00

**Table 3**  
Nutritional characterization of the three burger patties analysed.

Nutritional Components	Unit	Legume-based burger patty	Chicken burger patty	Beef burger patty
Protein Digestibility Corrected Amino Acid Score (PDCAAS)		0.78	0.94	0.94
Protein	g/100 g	6.13	21.18	20.09
Total dietary fibre	g/100 g	3.73	/	/
Soluble dietary fibre	g/100 g	0.79	/	/
Insoluble dietary fibre	g/100 g	2.94	/	/
Saturated fatty acids (SFA)	g/100 g	0.61	3.81	2.16
Monounsaturated fatty acids	g/100 g	1.06	2.05	2.22
Polyunsaturated fatty acids (PUFA)	g/100 g	0.80	0.79	1.52
PUFA/SFA ratio		1.63	0.21	0.70
Cholesterol	mg/100 g	1.94	57.82	78.94
Carbohydrates	g/100 g	17.84	/	/
Simple sugars	g/100 g	0.66	/	/
Phytic acid	g/100 g	0.51	/	/

inclusion in the system of the stages that follow the production gate: distribution, retail, and home storage, and final preparation (heating or cooking). Fig. 2 provides an overview of the entire life cycle analysed.

## 2.2. Life cycle inventory

This section provides data on the production of the three burger patties, including raw material cultivation, farming activities and their transformation. The data was obtained through direct interviews with the R&D team of the Matarrese company involved in food process design. To simplify the inventory phase, the three burger patties are analysed separately.

Primary data were used for all quantities and processes involved in the transformation of raw materials into final products, i.e. burger patties. The recipes provided by the company Matarrese characterize the different products in terms of composition (Table 2).

According to the Secretariat of the Codex Alimentarius Commission [26], the definition of food is made by the characteristic of providing nutrients and energy to humans through the consumption of the same food, it is fundamental to also consider the nutritional characterization

of the products analysed. Concerning the composition of the three burgers, the Matarrese company also provided a characterization of the products from a nutritional point of view. Table 3 shows the nutritional details of the patties.

Secondary data from Ecoinvent 3.8 were used for the cultivation and farming activities (contextualized in the Italian scenario) to obtain datasets related to the production of ingredients for each of the burger patties analysed. In the case of transport from the production site of the raw materials to the transformation site, an average distance by truck of 500 km was quantified, also according to the PCRs published by EPD International [27].

### 2.2.1. Legume-based burger patty production inventory

The recipe for the legume-based burger patty and the production flowchart are the result of the Le.Ge.Re.Te project [28]. The ingredients are black chickpeas, spinach, pearl barley, cheese, oil, egg whites, water, and corn starch as shown in Table 2.

The Matarrese company has provided primary data on the type and model of machines, number, time, process temperature, and mass flow rate for the batch production process, which has a steady-state productivity of 200 kg/h (2000 patties/h).

According to the mass flow diagram in Fig. 3, production starts with 28.4 kg of black chickpeas which, after cold storage (0), undergo a maceration process for 48 h in 284 l of water and a cooking process in an autoclave for 2 h 15 min (2a). The cooked product is then ground in a mixer for 3 min (3a) and chilled in a blast chiller for 3 min at  $-3^{\circ}\text{C}$  (4a).

At the same time, 7.1 kg of spinach, after cold storage (0), is cooked for 15 min in 14.2 kg of water (2b), soaked and then mixed for 3 min (3b).

At the same time, 21.3 kg of pearl barley, after cold storage (0), is cooked in an autoclave with 355 kg of water for 15 min (2c), then mixed with a blender for 3 min (3c) and chilled in a blast chiller for 3 min at  $-3^{\circ}\text{C}$  (4b).

Vegetable products vary in weight as they absorb or release water during cooking, in particular, chickpeas increase their weight by 3.85 times, spinach loses 15 % of its weight, and pearl barley increases its weight by about 4 times. This variation in weight makes it possible to obtain 207.8 kg of dough per preparation cycle.

Once the cooked ingredients are obtained, they are mixed with 2.84 kg of cheese, 1.31 g of extra virgin olive oil, and 5 kg of egg whites. The mixing process (5) takes 15 min, and the dough obtained is then transferred to the next process (forming phase, 6) to obtain the patties. A loss of 7.8 kg of dough was quantified during the mixing and forming activities.

The pre-cooking process (7) requires the use of an oven to cook the patties at  $130^{\circ}\text{C}$  for 15 min. This is followed by a cooling phase at  $-3^{\circ}\text{C}$  for 6 min (8). The burger patty is then coated with 6 kg of a 2:1 water/starch solution (9) and baked again at  $210^{\circ}\text{C}$  for 25 min (10). The finished product is then stored (12) and vacuum skin packed (13). The packaging used is a 14.3 g packaging solution consisting of a multilayer lid (PE/EVA/EVOH) and a multilayer tray (PE/EVA/PET).

According to EPD International [27], an average distance of 500 km was representative of the Italian scenario analysed for Euro 5 lorry transport from the production site to the retail outlet.

According to Fricke & Becker [29], the average size of a retail refrigerator was assumed to be  $730 \times 100 \times 150$  cm (W  $\times$  L  $\times$  H) and the average consumption to be  $4.8 \times 10^{-6}$  kWh/cm<sup>3</sup>/day. Considering that the average volume of the packaging of the different systems analysed was 1.43 cm<sup>3</sup>, the allocated energy consumption per day was quantified as 0.0096 kWh/day.

Considering the shelf life of each packaging system and the average time the packaging spends at retail, 20 % of the shelf life was allocated to the retail stage [30].

The energy consumption of a consumer refrigerator was quantified as 300 kWh/year, while the relative capacity was quantified as 250 l. Based on the average volume of the packaging and the average energy

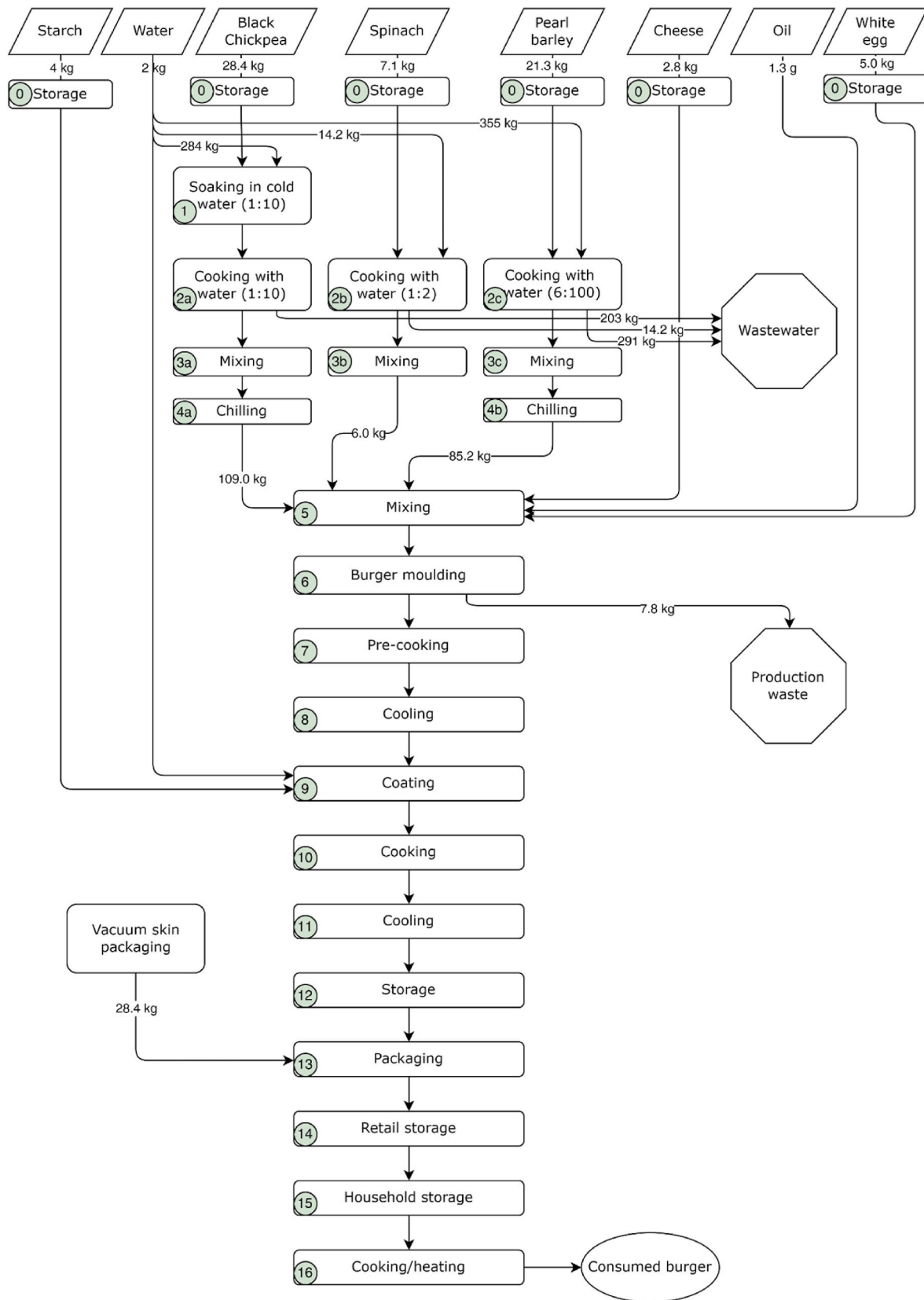


Fig. 3. Mass flow diagram related to the legume-based burger patty.

**Table 4**  
Details of the different operations involved in the burger patty production.

Operation	Process	Machine	No. of machines	Power (kW)	Description	Time (h)	Final energy consumption	Unit
0	Storage	Cool store	2	0.41	Stock capacity: 1400 dm <sup>3</sup> Usability factor: 0,5	24	168.69	Wh/ dm <sup>3</sup>
1	Maceration	Container	1	–		48	–	0
2a	Cooking	Autoclave	2	13.50	Capacity: 150l	2.25	405.00	Wh/l
2b	Cooking	Autoclave	1	13.50	Capacity: 150l	0.25	22.50	Wh/l
2c	Cooking	Autoclave	1	13.50	Capacity: 150l	0.25	22.50	Wh/l
3a	Mixing	Cutter	1	11.00	Productivity: 36 kg/cycle	0.05	15.28	Wh/kg
3b	Mixing	Cutter	1	11.00	Productivity: 36 kg/cycle	0.05	15.28	Wh/kg
3c	Mixing	Cutter	1	11.00	Productivity: 36 kg/cycle	0.05	15.28	Wh/kg
4a	Chilling	Blast chiller	1	7.10	Productivity: 70 kg/cycle	0.05	5.07	Wh/kg
4b	Chilling	Blast chiller	1	7.10	Productivity: 70 kg/cycle	0.05	5.07	Wh/kg
5	Mixing	Mixer	1	2.50	Productivity: 160 kg/cycle	0.25	7.81	Wh/kg
6	Burger patty moulding	Moulder	1	1.00	Productivity: 2100 patties/h	0.05	0.24	Wh/kg
7	Pre-cooking	Oven	2	31.80	Capacity: 250 patties Usability factor: 0,8	0.25	508.80	Wh/kg
8	Cooling	Blast chiller	2	7.10	Capacity: 700 patties	0.1	20.29	Wh/kg
9	Coating	Batter breading machine	1	1.20	Productivity: 2000 patties/h	0.25	1.50	Wh/kg
10	Cooking	Oven	2	31.80	Productivity: 250 burger patties Usability factor: 0,8	0.3	610.56	Wh/kg
11	Cooling	Blast chiller	2	7.10	Capacity: 700 patties	0.1	20.29	Wh/kg
12	Storage	Cool store	2	0.41	Capacity: 14000 patties Usability factor: 0,5	24	168.69	Wh/kg
13	Packaging	Thermo-former	1	15.00	Productivity: 6 cycles/min 2 burger patty/cycle	1	208.33	Wh/kg
14	Retail storage	Retail refrigerator	1	2.00	730 × 100 × 150 cm 4.8 × 10 <sup>-6</sup> kWh/cm <sup>3</sup> /day	1	4.80 × 10 <sup>-09</sup>	Wh/ cm <sup>3</sup>
15	Household storage	Fridge	1	1.00	365 kWh/year 250 l capacity	1	1.88 × 10 <sup>-08</sup>	Wh/l
16	Heating	Hob	1	1.00	Heating time: 3 min	1	500.00	Wh/kg

consumption per day of the refrigerator, the average energy consumption per packaging was quantified as 0.0047 kWh/day.

According to the shelf life of each packaging solution and the average time spent in the retail store, 80 % of the shelf life was allocated to home preservation [30].

According to the information provided by Matarrese, the consumer heats the product in the pan for 3 min to get it ready for consumption. To model this phase, the use of a 1.5 kW domestic induction hob was assumed. No packaging waste scenario was analysed. Further, Table 4 details different operations in the burger patty production.

### 2.2.2. Meat-based burger patty production inventory

Matarrese, the company provided primary data on the recipe and production process for the two meat burger patties (beef and chicken). The differences between the beef and chicken burger patties are only in the raw materials used: the beef burger patty requires beef and salt, while the chicken burger patty recipe implies the use of chicken meat, cheese, and salt, as shown in Table 2. The technology, machinery, and processes for both beef and chicken-based patties are the same.

In order to compare the different products obtained with the same level of technology, the Matarrese company also provided primary data on the type and model of machinery, number, time, process temperature and mass flow rate for the production of meat-based burger patties. The production was 2000 patties/h with a steady state productivity of 200 kg/h.

According to the mass flow diagram in Fig. 4, the production processes for the beef and chicken-based patties are the same, the only difference being the addition of cheese in the mixing phase for the chicken-based patty.

The meat is stored in refrigerated cells and after selection of pieces, the meat is mixed with salt for 3 min (5). While mixing, cheese (18 %) is added only to the chicken burger patty and salt (2 %) to both. The burger patties are then formed (6) and chilled in a blast chiller for 6 min at

–3 °C (8). The finished product is then vacuum skin packaged (13). The packaging used is a 14.3 g packaging solution consisting of a multilayer lid (PE/EVA/EVOH) and a multilayer tray (PE/EVA/PET).

The inventory for the meat-based burger patty production mirrors the methodology used in the legume-based burger patty inventory. It includes the same stages of transportation, retail storage, and home preservation, as outlined previously.

For reheating by the consumer (16), according to the information provided by Matarrese, 10 min are needed in the pan to get the product ready for consumption. To model this phase, the use of a 1.5 kW domestic induction hob was assumed. No packaging waste scenario was analysed. Further, Table 5 details different operations in meat burger patty production.

### 2.3. Life cycle impact assessment

In line with the objective of the study, the impact assessment methodology used was CML-IA baseline (V3.09), an LCA methodology developed by the Centre of Environmental Science (CML) of Leiden University in the Netherlands. The CML-IA baseline method is used because it simplifies the process by focusing on a set of key impact categories that are most relevant to the study's goals. This focus reduces complexity and improves efficiency, ensuring a clear and manageable evaluation of environmental impacts. By using fewer but more critical categories, the method allows for a more precise and targeted analysis, which is crucial for drawing meaningful conclusions about the sustainability of products.

The environmental impacts were analysed using SimaPro 9.4.0.2 software (Pré Sustainability, Amersfoort, The Netherlands) and the Eco-invent database v 3.8 according to cut-off allocation criteria.

The LCIA phase aims to quantify the magnitude of potential environmental impacts using Life Cycle Inventory Analysis data; it consists of associating inventory data on pollutants with specific environmental

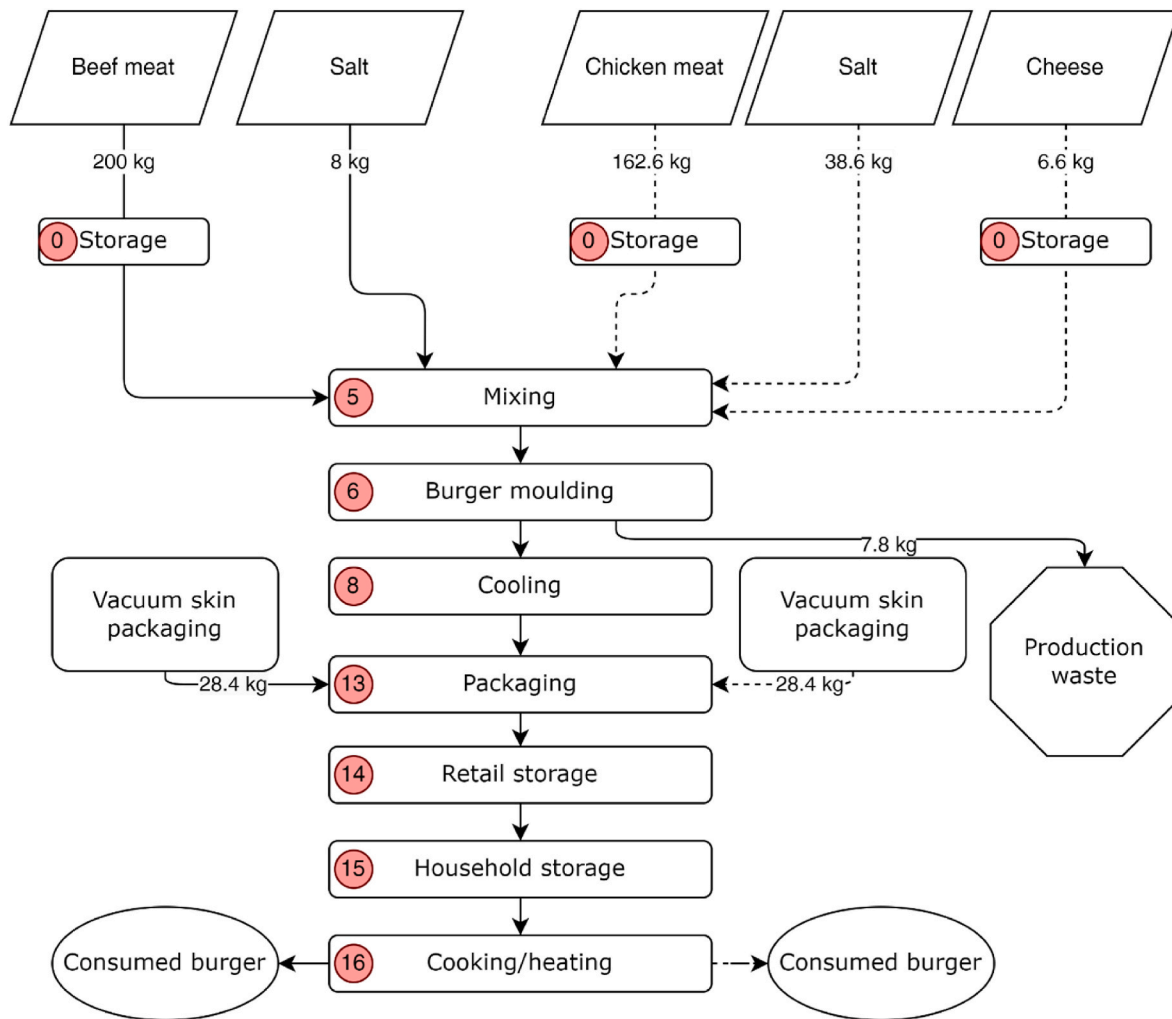


Fig. 4. Mass flow diagram related to the meat-based burger patty.

**Table 5**  
Details of the different energy operations involved in burger patty production.

Operation	Process	Machine	No. of machines	Power (kW)	Description	Time (h)	Final energy consumption	Unit
0	Storage	Cool store	2	0.41	Stock capacity: 1400 dm <sup>3</sup> Usability factor: 0,5	24	168.69	Wh/dm <sup>3</sup>
5	Mixing	Mixer	1	2.50	Productivity: 160 kg/cycle	0.25	7.81	Wh/kg
6	Burger patty moulding	Moulder	1	1.00	Productivity: 2100 patties/h	0.05	0.24	Wh/kg
8	Cooling	Blast chiller	2	7.10	Capacity: 700 patties	0.1	20.29	Wh/kg
13	Packaging	Thermoformer	1	15.00	Productivity: 6 cycles/min 2 burger patty/cycle	1	208.33	Wh/kg
14	Retail storage	Retail refrigerator	1	2.00	730 × 100 × 150 cm 4.8 × 10 <sup>-6</sup> kWh/cm <sup>3</sup> /day	1	4.80x10 <sup>-09</sup>	Wh/cm <sup>3</sup>
15	Household storage	Fridge	1	1.00	365 kWh/year 250 l capacity	1	1.88x10 <sup>-08</sup>	Wh/l
16	Cooking	Hob	1	1.00	Heating time: 10 min	1	1600.00	Wh/kg

impact categories. The impact categories, the relative units and the acronyms used are summarized in Table 6.

2.3.1. Economic analysis

The economic analysis in this study was conducted by integrating multiple data sources to ensure a comprehensive and contextualized assessment of affordability. First, household expenditure data on beef and veal meat for Italy in 2021 were obtained from Statista [31]. To

account for economic changes, these values were adjusted for inflation using the annual inflation rates reported by the International Monetary Fund (IMF) [32] for the years 2022 (8.2%), 2023 (5.6%), and 2024 (2.5%). To contextualize the affordability analysis, we also gathered the average household size in Italy for 2023 from ISTAT [33].

Next, the cost per product were mapped from major Italian supermarket chains [34–36], by sourcing data from their official online catalogues. These prices were filtered for beef, chicken, and legume burger

**Table 6**  
Environmental impact categories, acronyms, and units of the CML method.

Parameters	Acronyms	Units
Abiotic depletion	AD	kg Sb <sub>eq</sub>
Abiotic depletion (fossil fuels)	ADF	MJ
Global warming (GWP100a)	GWP	kg CO <sub>2, eq</sub>
Ozone layer depletion (ODP)	OLD	kg CFC-11 <sub>eq</sub>
Human toxicity	HT	kg 1.4-DB <sub>eq</sub>
Fresh water aquatic ecotoxicity.	FWE	kg 1.4-DB <sub>eq</sub>
Marine aquatic ecotoxicity	MAE	kg 1.4-DB <sub>eq</sub>
Terrestrial ecotoxicity	TE	kg 1.4-DB <sub>eq</sub>
Photochemical oxidation	PO	kg C <sub>2</sub> H <sub>4eq</sub>
Acidification	ACID	kg SO <sub>2eq</sub>
Eutrophication	EUT	kg PO <sub>3<sup>7</sup>4eq</sub>

patties, and the average price per 100 g of each product was calculated to ensure consistency in comparison. While overall price variations across brands and regions were minimal, slight differences were observed for gourmet and organic (bio) products, which exhibited slightly higher prices due to their premium nature. These variations were inherent to the product category and were accounted for by averaging the price data, ensuring a standardized economic assessment across all products.

Additionally, the affordability Index of these products was analysed in terms of units/week/person for the Italian scenario, providing insights into the economic accessibility of each option in the average Italian household.

$$\text{Affordability Index} = \frac{\text{Average weekly expenditure on meat per person}}{\text{Average cost of a burger patty at the supermarket chain}}$$

Further, normalization of the affordability index provides a clear comparison of each product's affordability relative to the most affordable option. This approach highlights cost accessibility, supporting informed decision-making based on value through the affordability factor.

$$\text{Affordability factor per FU} = \frac{\text{Affordability Index}}{\text{Minimum of Affordability indices}}$$

### 3. Results and discussion

As shown in the Life Cycle Inventory analysis, the environmental impacts are associated with different stages of the burger patty production process. These stages include raw materials, packaging, processing, heating, and consumption for each of the burger patties, i.e. legume, chicken, and beef. This approach provides a comprehensive understanding of the life cycle of a product.

In the following Table 7, all operations involved in the burger patties are broadly classified as upstream, core and downstream as per system boundaries. The combined results indicate that the main impacts are in the upstream, mainly due to the production of raw materials for the burger patty preparations. As reported in detail in the supplementary data file (SD1), the main contributors to the upstream phase of the legume-based burger patty are, on average across all impact categories, chickpeas (23.9 %), eggs (9.6 %), barley (7.6 %) and olive oil (6.4 %). Similarly, in SD2, the main contributors to the upstream phase of the chicken-based burger patty are chicken meat (56 %) and cheese (27.7 %) on average across all impact categories. For the beef-based burger patty (reported in SD3), the main contributor is beef with an average of more than 95 % across all impact categories. This finding highlights the importance of sustainable sourcing and responsible production.

From the results based on DU, the burger patty based on legume raw materials are more environmentally sustainable than meat-based burger patties. These results are in line with those from literature studies comparing different burgers, such as [5,10,37]. A life cycle analysis of a legume-based burger patty found that it generated significantly less

**Table 7**  
Environmental impacts based on the phases of the burger patties with mass DU 100g.

Food type	Phase	AD (kg Sb eq)	ADF (MJ)	GWP (kg CO <sub>2</sub> eq)	OLD (kg CFC-11 eq)	HT (kg 1,4-DB eq)	FWE (kg 1,4-DB eq)	MAE (kg 1,4-DB eq)	TE (kg 1,4-DB eq)	PO (kg C <sub>2</sub> H <sub>4</sub> eq)	ACID (kg SO <sub>2</sub> eq)	EUT (kg PO <sub>3<sup>7</sup>4</sub> eq)
Chicken Legume	Upstream	1.71	2.91x10 <sup>-1</sup>	3.69x10 <sup>-1</sup>	1.79x10 <sup>-8</sup>	5.71x10 <sup>-1</sup>	1.82x10 <sup>-1</sup>	8.05x10 <sup>-1</sup>	1.22x10 <sup>-2</sup>	3.54x10 <sup>-5</sup>	3.44x10 <sup>-3</sup>	1.36x10 <sup>-3</sup>
		2.29x10 <sup>-7</sup>	2.91x10 <sup>-1</sup>	4.77x10 <sup>-2</sup>	3.28x10 <sup>-9</sup>	2.99x10 <sup>-2</sup>	1.55x10 <sup>-2</sup>	2.11x10 <sup>-1</sup>	1.43x10 <sup>-3</sup>	1.01x10 <sup>-5</sup>	4.52x10 <sup>-4</sup>	2.67x10 <sup>-4</sup>
Chicken Legume	Core	5.44x10 <sup>-6</sup>	1.20x10 <sup>-1</sup>	4.58	1.03x10 <sup>-7</sup>	6.60x10 <sup>-1</sup>	1.05	3.03x10 <sup>-3</sup>	8.43x10 <sup>-2</sup>	9.41x10 <sup>-4</sup>	3.12x10 <sup>-2</sup>	1.73x10 <sup>-2</sup>
		1.91x10 <sup>-8</sup>	1.19x10 <sup>-1</sup>	9.05x10 <sup>-3</sup>	1.10x10 <sup>-9</sup>	2.13x10 <sup>-3</sup>	2.37x10 <sup>-3</sup>	6.31	1.96x10 <sup>-5</sup>	1.74x10 <sup>-5</sup>	3.54x10 <sup>-5</sup>	9.06x10 <sup>-6</sup>
Chicken Legume	Distribution	9.55x10 <sup>-8</sup>	5.61x10 <sup>-1</sup>	4.29x10 <sup>-2</sup>	5.19x10 <sup>-9</sup>	1.05x10 <sup>-2</sup>	1.16x10 <sup>-2</sup>	3.02x10 <sup>-1</sup>	9.99x10 <sup>-5</sup>	8.25x10 <sup>-6</sup>	1.69x10 <sup>-4</sup>	4.62x10 <sup>-5</sup>
		1.91x10 <sup>-8</sup>	1.19x10 <sup>-1</sup>	9.05x10 <sup>-3</sup>	1.10x10 <sup>-9</sup>	2.13x10 <sup>-3</sup>	2.37x10 <sup>-3</sup>	6.31	1.96x10 <sup>-5</sup>	1.74x10 <sup>-5</sup>	3.54x10 <sup>-5</sup>	9.06x10 <sup>-6</sup>
Chicken Legume	Consumption	3.17x10 <sup>-8</sup>	1.39x10 <sup>-1</sup>	9.46x10 <sup>-3</sup>	1.68x10 <sup>-9</sup>	3.49x10 <sup>-3</sup>	1.61x10 <sup>-3</sup>	3.30	1.30x10 <sup>-5</sup>	1.30x10 <sup>-6</sup>	3.09x10 <sup>-5</sup>	7.03x10 <sup>-6</sup>
		3.17x10 <sup>-8</sup>	1.39x10 <sup>-1</sup>	9.46x10 <sup>-3</sup>	1.68x10 <sup>-9</sup>	3.49x10 <sup>-3</sup>	1.61x10 <sup>-3</sup>	3.30	1.30x10 <sup>-5</sup>	1.30x10 <sup>-6</sup>	3.09x10 <sup>-5</sup>	7.03x10 <sup>-6</sup>
Chicken Legume	Total	8.01x10 <sup>-8</sup>	4.71x10 <sup>-1</sup>	3.59x10 <sup>-2</sup>	4.36x10 <sup>-9</sup>	8.62x10 <sup>-3</sup>	9.68x10 <sup>-3</sup>	2.52x10 <sup>-1</sup>	8.34x10 <sup>-5</sup>	6.90x10 <sup>-6</sup>	1.41x10 <sup>-4</sup>	3.60x10 <sup>-5</sup>
		2.89x10 <sup>-8</sup>	1.70x10 <sup>-1</sup>	1.30x10 <sup>-2</sup>	1.57x10 <sup>-9</sup>	3.11x10 <sup>-3</sup>	3.49x10 <sup>-3</sup>	9.10	2.49x10 <sup>-6</sup>	3.01x10 <sup>-5</sup>	2.49x10 <sup>-6</sup>	5.08x10 <sup>-5</sup>
Chicken Legume	Total	8.01x10 <sup>-8</sup>	4.71x10 <sup>-1</sup>	3.59x10 <sup>-2</sup>	4.36x10 <sup>-9</sup>	8.62x10 <sup>-3</sup>	9.68x10 <sup>-3</sup>	2.52x10 <sup>-1</sup>	8.34x10 <sup>-5</sup>	6.90x10 <sup>-6</sup>	1.41x10 <sup>-4</sup>	3.60x10 <sup>-5</sup>
		9.08x10 <sup>-7</sup>	2.44	4.23x10 <sup>-1</sup>	2.50x10 <sup>-8</sup>	7.13x10 <sup>-2</sup>	1.96x10 <sup>-1</sup>	1.15x10 <sup>-2</sup>	4.53x10 <sup>-5</sup>	1.23x10 <sup>-2</sup>	4.53x10 <sup>-5</sup>	3.65x10 <sup>-3</sup>
Chicken Legume	Total	3.85x10 <sup>-7</sup>	1.16	1.13x10 <sup>-1</sup>	1.17x10 <sup>-8</sup>	4.10x10 <sup>-2</sup>	3.22x10 <sup>-2</sup>	6.36x10 <sup>-1</sup>	1.58x10 <sup>-3</sup>	2.22x10 <sup>-5</sup>	7.02x10 <sup>-4</sup>	3.33x10 <sup>-4</sup>
		5.57x10 <sup>-6</sup>	1.27x10 <sup>-1</sup>	4.64	1.10x10 <sup>-7</sup>	6.75x10 <sup>-1</sup>	1.06	3.06x10 <sup>-3</sup>	8.44x10 <sup>-2</sup>	9.51x10 <sup>-4</sup>	3.14x10 <sup>-2</sup>	1.74x10 <sup>-2</sup>

AD - Abiotic depletion; ADF - Abiotic depletion (fossil fuels); GWP - Global warming (GWP100a); OLD - Ozone layer depletion; HT - Human toxicity; FWE - Fresh water aquatic ecotoxicity; MAE - Marine aquatic ecotoxicity; TE - Terrestrial ecotoxicity; PO - Photochemical oxidation; ACID - Acidification; EUT - Eutrophication.

**Table 8**  
Environmental impacts of different burger patties based on the functional unit.

Functional unit	Burger	AD	ADF	GWP	OLD	HT	FWE	MAE	TE	PO	ACID	EUT
	Units	kg Sb eq	MJ	kg CO <sub>2</sub> eq	kg CFC-11 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg C <sub>2</sub> H <sub>4</sub> eq	kg SO <sub>2</sub> eq	kg PO <sub>4</sub> — eq
<b>Mass (100 g)</b>	Legume-based	3.85x10 <sup>-7</sup>	1.16	1.13x10 <sup>-1</sup>	1.17x10 <sup>-8</sup>	4.10x10 <sup>-2</sup>	3.22x10 <sup>-2</sup>	6.37x10 <sup>1</sup>	1.58x10 <sup>-3</sup>	2.22x10 <sup>-5</sup>	7.06x10 <sup>-4</sup>	3.34x10 <sup>-4</sup>
	Chicken	9.08x10 <sup>-7</sup>	2.44	4.23x10 <sup>-1</sup>	2.50x10 <sup>-8</sup>	7.13x10 <sup>-2</sup>	1.96x10 <sup>-1</sup>	1.15x10 <sup>2</sup>	1.23x10 <sup>-2</sup>	4.53x10 <sup>-5</sup>	3.65x10 <sup>-3</sup>	1.41x10 <sup>-3</sup>
	Beef	5.57x10 <sup>-6</sup>	1.27x10 <sup>1</sup>	4.64	1.10x10 <sup>-7</sup>	6.75x10 <sup>-1</sup>	1.06	3.06x10 <sup>3</sup>	8.44x10 <sup>-2</sup>	9.51x10 <sup>-4</sup>	3.14x10 <sup>-2</sup>	1.74x10 <sup>-2</sup>
<b>Energy (100 kcal)</b>	Legume-based	3.27x10 <sup>-7</sup>	9.85x10 <sup>-1</sup>	9.59x10 <sup>-2</sup>	9.94x10 <sup>-9</sup>	3.47x10 <sup>-2</sup>	2.73x10 <sup>-2</sup>	5.40x10 <sup>1</sup>	1.34x10 <sup>-3</sup>	1.88x10 <sup>-5</sup>	5.98x10 <sup>-4</sup>	2.83x10 <sup>-4</sup>
	Chicken	4.90x10 <sup>-7</sup>	1.31	2.29x10 <sup>-1</sup>	1.35x10 <sup>-8</sup>	3.85x10 <sup>-2</sup>	1.06x10 <sup>-1</sup>	6.22x10 <sup>1</sup>	6.65x10 <sup>-3</sup>	2.45x10 <sup>-5</sup>	1.97x10 <sup>-3</sup>	7.60x10 <sup>-4</sup>
	Beef	3.39x10 <sup>-6</sup>	7.76	2.83	6.70x10 <sup>-8</sup>	4.11x10 <sup>-1</sup>	6.47x10 <sup>-1</sup>	1.87x10 <sup>3</sup>	5.15x10 <sup>-2</sup>	5.80x10 <sup>-4</sup>	1.92x10 <sup>-2</sup>	1.06x10 <sup>-2</sup>
<b>Protein (1 g)</b>	Legume-based	6.29x10 <sup>-8</sup>	1.90x10 <sup>-1</sup>	1.85x10 <sup>-2</sup>	1.91x10 <sup>-9</sup>	6.69x10 <sup>-3</sup>	5.25x10 <sup>-3</sup>	1.04x10 <sup>1</sup>	2.57x10 <sup>-4</sup>	3.62x10 <sup>-6</sup>	1.15x10 <sup>-4</sup>	5.45x10 <sup>-5</sup>
	Chicken	4.29x10 <sup>-8</sup>	1.15x10 <sup>-1</sup>	2.00x10 <sup>-2</sup>	1.18x10 <sup>-9</sup>	3.37x10 <sup>-3</sup>	9.25x10 <sup>-3</sup>	5.44	5.82x10 <sup>-4</sup>	2.14x10 <sup>-6</sup>	1.72x10 <sup>-4</sup>	6.65x10 <sup>-5</sup>
	Beef	2.77x10 <sup>-7</sup>	6.34x10 <sup>-1</sup>	2.31x10 <sup>-1</sup>	5.47x10 <sup>-9</sup>	3.36x10 <sup>-2</sup>	5.28x10 <sup>-2</sup>	1.52x10 <sup>2</sup>	4.20x10 <sup>-3</sup>	4.74x10 <sup>-5</sup>	1.56x10 <sup>-3</sup>	8.65x10 <sup>-4</sup>
<b>Total dietary fibre (1 g)</b>	Legume-based	1.03x10 <sup>-7</sup>	3.12x10 <sup>-1</sup>	3.03x10 <sup>-2</sup>	3.14x10 <sup>-9</sup>	1.10x10 <sup>-2</sup>	8.63x10 <sup>-3</sup>	1.71x10 <sup>1</sup>	4.23x10 <sup>-4</sup>	5.95x10 <sup>-6</sup>	1.89x10 <sup>-4</sup>	8.95x10 <sup>-5</sup>
	Chicken	0	0	0	0	0	0	0	0	0	0	0
	Beef	0	0	0	0	0	0	0	0	0	0	0
<b>Saturated fatty acids (1 g)</b>	Legume-based	6.32x10 <sup>-7</sup>	1.90	1.86x10 <sup>-1</sup>	1.92x10 <sup>-8</sup>	6.72x10 <sup>-2</sup>	5.28x10 <sup>-2</sup>	1.04x10 <sup>2</sup>	2.59x10 <sup>-3</sup>	3.64x10 <sup>-5</sup>	1.16x10 <sup>-3</sup>	5.47x10 <sup>-4</sup>
	Chicken	2.38x10 <sup>-7</sup>	6.39x10 <sup>-1</sup>	1.11x10 <sup>-1</sup>	6.57x10 <sup>-9</sup>	1.87x10 <sup>-2</sup>	5.14x10 <sup>-2</sup>	3.03x10 <sup>1</sup>	3.24x10 <sup>-3</sup>	1.19x10 <sup>-5</sup>	9.58x10 <sup>-4</sup>	3.69x10 <sup>-4</sup>
	Beef	2.58x10 <sup>-6</sup>	5.89	2.15	5.09x10 <sup>-8</sup>	3.12x10 <sup>-1</sup>	4.91x10 <sup>-1</sup>	1.42x10 <sup>3</sup>	3.91x10 <sup>-2</sup>	4.40x10 <sup>-4</sup>	1.45x10 <sup>-2</sup>	8.05x10 <sup>-3</sup>
<b>Monounsaturated fatty acids (1 g)</b>	Legume-based	3.63x10 <sup>-7</sup>	1.10	1.07x10 <sup>-1</sup>	1.11x10 <sup>-8</sup>	3.87x10 <sup>-2</sup>	3.04x10 <sup>-2</sup>	6.01x10 <sup>1</sup>	1.49x10 <sup>-3</sup>	2.09x10 <sup>-5</sup>	6.66x10 <sup>-4</sup>	3.15x10 <sup>-4</sup>
	Chicken	4.43x10 <sup>-7</sup>	1.19	2.07x10 <sup>-1</sup>	1.22x10 <sup>-8</sup>	3.48x10 <sup>-2</sup>	9.55x10 <sup>-2</sup>	5.62x10 <sup>1</sup>	6.01x10 <sup>-3</sup>	2.21x10 <sup>-5</sup>	1.78x10 <sup>-3</sup>	6.87x10 <sup>-4</sup>
	Beef	2.51x10 <sup>-6</sup>	5.73	2.09	4.95x10 <sup>-8</sup>	3.04x10 <sup>-1</sup>	4.78x10 <sup>-1</sup>	1.38x10 <sup>3</sup>	3.80x10 <sup>-2</sup>	4.29x10 <sup>-4</sup>	1.42x10 <sup>-2</sup>	7.83x10 <sup>-3</sup>
<b>Polyunsaturated fatty acids (1 g)</b>	Legume-based	4.82x10 <sup>-7</sup>	1.45	1.41x10 <sup>-1</sup>	1.47x10 <sup>-8</sup>	5.12x10 <sup>-2</sup>	4.02x10 <sup>-2</sup>	7.96x10 <sup>1</sup>	1.97x10 <sup>-3</sup>	2.77x10 <sup>-5</sup>	8.83x10 <sup>-4</sup>	4.17x10 <sup>-4</sup>
	Chicken	1.15x10 <sup>-6</sup>	3.08	5.36x10 <sup>-1</sup>	3.17x10 <sup>-8</sup>	9.03x10 <sup>-2</sup>	2.48x10 <sup>-1</sup>	1.46x10 <sup>2</sup>	1.56x10 <sup>-2</sup>	5.74x10 <sup>-5</sup>	4.62x10 <sup>-3</sup>	1.78x10 <sup>-3</sup>
	Beef	3.66x10 <sup>-6</sup>	8.37	3.05	7.23x10 <sup>-8</sup>	4.44x10 <sup>-1</sup>	6.98x10 <sup>-1</sup>	2.01x10 <sup>3</sup>	5.55x10 <sup>-2</sup>	6.26x10 <sup>-4</sup>	2.07x10 <sup>-2</sup>	1.14x10 <sup>-2</sup>
<b>Cholesterol (1 mg)</b>	Legume-based	1.99x10 <sup>-7</sup>	5.99x10 <sup>-1</sup>	5.83x10 <sup>-2</sup>	6.05x10 <sup>-9</sup>	2.11x10 <sup>-2</sup>	1.66x10 <sup>-2</sup>	3.28x10 <sup>1</sup>	8.13x10 <sup>-4</sup>	1.14x10 <sup>-5</sup>	3.64x10 <sup>-4</sup>	1.72x10 <sup>-4</sup>
	Chicken	1.15x10 <sup>-8</sup>	3.09x10 <sup>-2</sup>	5.36x10 <sup>-3</sup>	3.17x10 <sup>-10</sup>	9.04x10 <sup>-4</sup>	2.48x10 <sup>-3</sup>	1.46	1.56x10 <sup>-4</sup>	5.74x10 <sup>-7</sup>	4.63x10 <sup>-5</sup>	1.78x10 <sup>-5</sup>
	Beef	9.63x10 <sup>-8</sup>	2.20x10 <sup>-1</sup>	8.02x10 <sup>-2</sup>	1.90x10 <sup>-9</sup>	1.17x10 <sup>-2</sup>	1.84x10 <sup>-2</sup>	5.30x10 <sup>1</sup>	1.46x10 <sup>-3</sup>	1.65x10 <sup>-5</sup>	5.43x10 <sup>-4</sup>	3.01x10 <sup>-4</sup>
<b>Carbohydrates (1 g)</b>	Legume-based	2.16x10 <sup>-8</sup>	6.51x10 <sup>-2</sup>	6.34x10 <sup>-3</sup>	6.58x10 <sup>-10</sup>	2.30x10 <sup>-3</sup>	1.80x10 <sup>-3</sup>	3.57	8.84x10 <sup>-5</sup>	1.24x10 <sup>-6</sup>	3.96x10 <sup>-5</sup>	1.87x10 <sup>-5</sup>
	Chicken	0	0	0	0	0	0	0	0	0	0	0
	Beef	0	0	0	0	0	0	0	0	0	0	0
<b>Simple sugars (1 g)</b>	Legume-based	5.84x10 <sup>-7</sup>	1.76	1.72x10 <sup>-1</sup>	1.78x10 <sup>-8</sup>	6.21x10 <sup>-2</sup>	4.88x10 <sup>-2</sup>	9.65x10 <sup>1</sup>	2.39x10 <sup>-3</sup>	3.36x10 <sup>-5</sup>	1.07x10 <sup>-3</sup>	5.06x10 <sup>-4</sup>
	Chicken	0	0	0	0	0	0	0	0	0	0	0
	Beef	0	0	0	0	0	0	0	0	0	0	0
<b>Nutrient-rich food Index (NRF)</b>	Legume-based	1.14x10 <sup>-6</sup>	3.44	3.35x10 <sup>-1</sup>	3.47x10 <sup>-8</sup>	1.21x10 <sup>-1</sup>	9.53x10 <sup>-2</sup>	1.89x10 <sup>2</sup>	4.67x10 <sup>-3</sup>	6.57x10 <sup>-5</sup>	2.09x10 <sup>-3</sup>	9.88x10 <sup>-4</sup>
	Chicken	1.54x10 <sup>-6</sup>	4.13	7.18x10 <sup>-1</sup>	4.24x10 <sup>-8</sup>	1.21x10 <sup>-1</sup>	3.32x10 <sup>-1</sup>	1.95x10 <sup>2</sup>	2.09x10 <sup>-2</sup>	7.69x10 <sup>-5</sup>	6.19x10 <sup>-3</sup>	2.39x10 <sup>-3</sup>
	Beef	5.84x10 <sup>-6</sup>	1.34x10 <sup>1</sup>	4.86	1.15x10 <sup>-7</sup>	7.08x10 <sup>-1</sup>	1.11	3.21x10 <sup>3</sup>	8.85x10 <sup>-2</sup>	9.98x10 <sup>-4</sup>	3.29x10 <sup>-2</sup>	1.82x10 <sup>-2</sup>

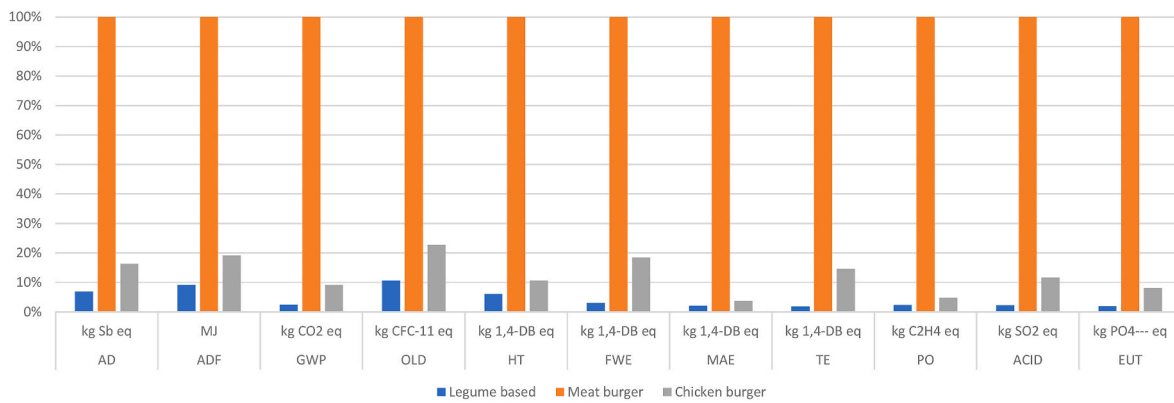


Fig. 5. Environmental impact comparison among burger patties with mass DU 100g.

AD - Abiotic depletion; ADF - Abiotic depletion (fossil fuels); GWP - Global warming (GWP100a); OLD - Ozone layer depletion; HT - Human toxicity; FWE - Fresh water aquatic ecotoxicity; MAE - Marine aquatic ecotoxicity; TE - Terrestrial ecotoxicity; PO - Photochemical oxidation; ACID - Acidification; EUT - Eutrophication.

greenhouse gas emissions, required less energy, had less impact on land use and used less water compared to meat-based patties. In line with the aim of the paper, a switch from DU to n-FU is proposed in the following Table 8 to illustrate the variation in results depending on the reference unit used in the study.

After analyzing the trends of the different impact categories, it can be seen from Fig. 5 and Table 8 that the trend is similar for all impact categories.

As GWP is a well-known impact category, it is proposed to focus on this impact category in Fig. 6a. The trend reported for the GWP impact category is representative of the trend for products in each impact category, allowing consistent emissions assessments and comparisons of the relative greenhouse gas impacts of different products.

The Supplementary Tables (SD5) indicate that, for meat-based burger patties made from chicken and beef, a significant portion of the overall environmental impact arises from upstream emissions, particularly those associated with livestock rearing and the energy inputs required during the animal-raising phase. These emissions are notably higher in the upstream stage compared to the core production phase and downstream processes.

In comparison, emissions from the legume-based burger patty are present across upstream, core, and downstream stages, as shown in Fig. 6b. This distribution highlights the distinct life cycle profiles of plant- and meat-based products and the substantial impact of early-stage activities in meat production.

As the primary function of food is its ability to provide nutrients for the body, this function is not adequately represented in a mass-based DU and alternatives have emerged in recent years [18]. Table 8 addressed this by presenting the environmental profiles of various burger patties in relation to specific nutritional parameters such as energy (kcal); protein (g); total dietary fibre (g); saturated fatty acids (g); monosaturated fatty acids (g); poly-saturated fatty acids (g); cholesterol (mg); carbohydrates (g); simple sugars (g) and finally the FU based on composite indicators derived from several nutrients, the Nutritionally Rich Food Index (NRF).

It is evident that these results provide some interesting insights to further discuss and interpret the implications of the different n-FU's considered in the study.

Across all impact categories, there is an increasing trend from legume-based patties to beef-based patties, primarily due to the processes involved in their preparation chain. For instance, considering one such n-FU, protein content, while the total protein content in chicken-based patties is higher than that in beef-based patties, the global warming potential (GWP) of chicken-based patties is lower compared to beef-based patties. These findings underscore the complex relationship between protein content and environmental impact, emphasizing the importance of considering the entire production process when assessing sustainability in food systems.

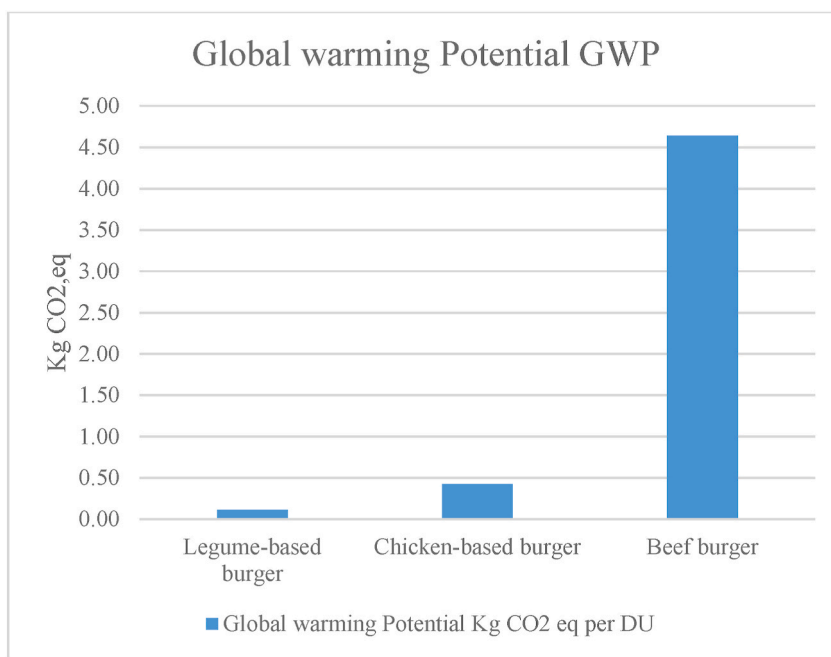
These results demonstrate two things: (i) the environmental impact associated with each nutrient unit does not consider the broader nutritional context and (ii) macro- and micronutrients cannot be considered individually because when food is consumed it cannot be broken down by nutrients.

The NRF index for each product analysed is calculated according to the modified formula in section 2.1.1. In the case of the legume burger patty, the NRF is 0.32; in the case of the chicken burger patty, the NRF is 0.59; and in the case of the beef burger patty, the NRF is 0.95, highlighting a nutritional gap between plant-based and animal-based options. While the legume patty offers significant environmental benefits, its lower NRF suggests potential deficiencies in certain essential nutrients when compared to beef. The beef-based patty, with its high NRF score, reflects the significant amount of protein it contains, while the PDCAAS (Table 3) complements this by confirming that beef protein is of high quality, complete, and easily digestible. Furthermore, the nutritional profile of the beef patty is highly favorable, with lower simple carbohydrates and sugars, as meat primarily consists of proteins and fats, with negligible carbohydrates or sugars naturally present.

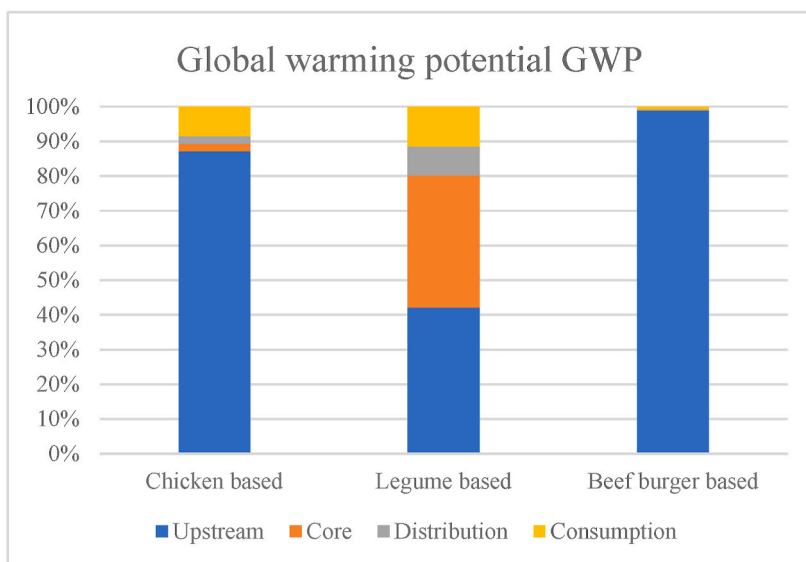
In contrast, the legume burger has the lowest environmental impact and the lowest protein content per serving of the options. To achieve the same protein content as beef with a legume-based burger, two and a half more patties would need to be consumed, resulting in twice the energy intake, but with a lower environmental footprint than the beef burger patty. This emphasizes the importance of dietary diversity in addressing nutritional gaps. A diversified diet, incorporating a variety of nutrient-dense plant-based foods alongside other protein sources, can help balance these deficiencies. Therefore, a diverse diet combining plant-based proteins with other nutrient-dense foods like nuts, seeds, and grains can ensure optimal nutrition without compromising on environmental or economic factors. Policymakers could promote such diversity through public health initiatives and food system reforms, encouraging consumers to make choices that balance health, sustainability, and cost.

### 3.1. Economic analysis results

According to Statista [31], the average monthly household expenditure on beef and veal meat in Italy from 2014 to 2021 is €31.69. After adjusting for inflation rates of 8.2 % (2022), 5.6 % (2023) and 2.5 % (2024) as reported on IMF data [32], the expenditure increases to approximately €37 in 2024. Additionally, the average household size in Italy in 2023 is reported to be 2.25, according to ISTAT [33]. The results, shown in Table 9, display the cost per functional unit, alongside GWP (kg CO<sub>2</sub> eq). GWP was selected as the primary environmental indicator due to its direct relevance in assessing climate change impacts, which are central to sustainability discussions and consumer awareness regarding food choices [38].



Global warming potential (GWP) scores of burger patties expressed per 100g (declared unit)



Environmental profile of burger patties along with Climate change impact indicator.

Fig. 6. a Global warming potential (GWP) scores of burger patties expressed per 100g (declared unit); b Environmental profile of burger patties with Climate change impact indicator.

The analysis focused on mass (100 g), energy (100 kcal), and the Nutrient-Rich Food (NRF) Index as functional units, excluding other micronutrient-based FUs. This choice was made because mass and energy are standard units that are easy to compare across food products, and the NRF Index provides a comprehensive measure of nutritional quality. Other nutrient FUs were excluded to avoid overcomplicating the analysis and to maintain a focus on the most relevant factors for both environmental and nutritional assessments.

The affordability index (units/week/person) reflects how accessible each patty type is for the average Italian consumer based on different functional units, offering a multidimensional perspective that includes both economic and environmental factors. In the SD7 of supplementary

data, additional information on other individual nutrient parameters is provided, enhancing the affordability index (units/week/person) that reflects how accessible each patty type is for the average Italian consumer. The legume-based patty had the highest cost but the lowest GWP among the patties, resulting in an affordability index of 3.87 units/week/person. In contrast, the meat patties were the most affordable with higher GWP and the better affordability index of 4.86 units/week/person as shown in Table 9.

Fig. 7 suggests that while consumers may find meat options like beef and chicken more affordable, these choices come with higher environmental impacts, particularly in terms of GWP.

The affordability factor indicates that, despite better nutritional and

**Table 9**

Average cost per FU of beef, chicken, and legume burger patties, including GWP (kg CO<sub>2</sub> eq) and affordability units/week/person and affordability factor in the Italian context.

Functional unit	Burger patty	GWP (kg CO <sub>2</sub> eq)	Average cost €/Unit	Affordability (n)/week/person	Affordability factor
Mass (100 g)	Legume-based	0.11	1.07	3.87	1.00
	Chicken	0.42	0.85	4.86	1.26
	Beef	4.64	0.91	4.53	1.17
Energy (100 kcal)	Legume-based	0.10	0.90	4.57	1.00
	Chicken	0.23	0.58	7.17	1.57
	Beef	2.83	0.65	6.35	1.39
Nutrient-rich food Index (1)	Legume-based	0.34	3.11	1.33	1.00
	Chicken	0.72	1.37	3.01	2.27
	Beef	4.86	0.94	4.40	3.31

environmental profile of legume-based patties, they could be less affordable for budget-conscious consumers. This scenario emphasizes the trade-off consumers must make, balancing nutritional requirements, affordability, and environmental considerations. The findings of this study align with previous LCA research, such as Detzel et al., 2022 [10] and Tang et al., 2024 [19], reinforcing the lower environmental impact of plant-based alternatives. Detzel et al. highlights the sustainability of legume-based extrudates, supporting our results on legume patties, while Tang et al. show a 65 % reduction in GHG emissions for Plant-Based Meat Analogues (PBMA), consistent with our LCA findings.

As legume-based options offer better sustainability & balanced nutritional profile, there is a critical opportunity for policymakers to incentivize the sustainable options and promote education and awareness to help consumers make informed choices potentially shifting towards more environmentally friendly alternatives while still meeting their nutritional needs. Denmark proposed climate tax on high-emission foods [39], alongside subsidies for plant-based alternatives, and Canada’s Food Guide [40], available in many languages prioritizes plant-based proteins, are exemplary policies and should be considered by other country policymakers to encourage sustainable consumption and informed dietary choices.

**3.2. Limitations**

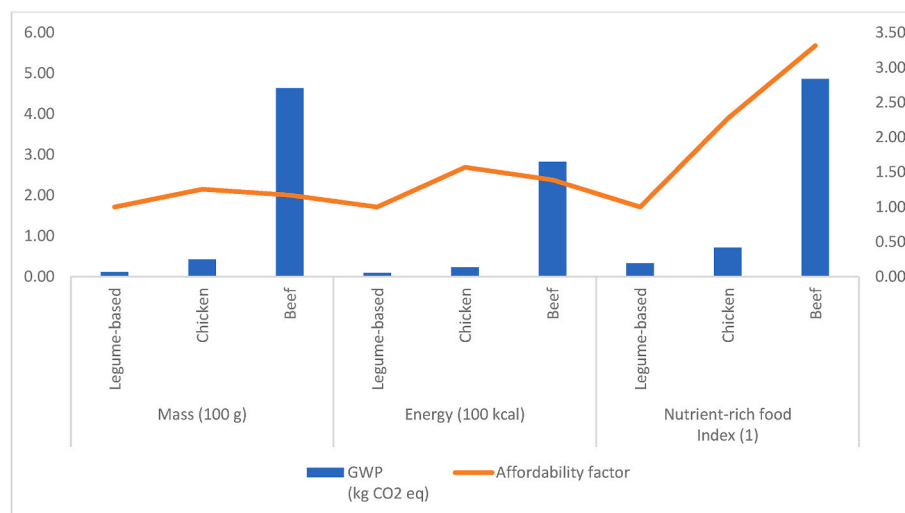
It is important to consider the limitations to interpret the results

accurately. Understanding these limitations is essential for a full assessment of the conclusions and implications of the study. In the NRF Index methodology, nutrient profiling must be performed with a careful literature review, as the introduction of all nutritional factors at once makes such data comparison difficult. The Recommended Intake Value (RIV) for the population could vary from meal to meal, and the present study did not take into account variations in nutrient requirements based on gender, age, and physical activity while maintaining a consistent daily caloric intake for the population. Nutrient changes during food storage, distribution, and preparation were also excluded from the study. Considering beef as an example, it might be interesting to explore breeding stages and include factors related to how livestock is raised, the ingredients of feeds, and the use of renewable energies, observing how these variations can influence both the environmental impact of the final product and its nutritional profile.

Furthermore, the accuracy of the findings relies heavily on the availability and quality of data regarding nutritional profiles, environmental impacts, and economic factors; any gaps or inconsistencies in data can affect reliability. The study focuses on the Italian context, which may not be representative of other regions or countries where different dietary habits and agricultural practices exist. Assumptions in cost calculations, such as uniform pricing across different supermarkets, could also influence economic conclusions. Additionally, the analysis primarily reflects short-term expenditures and impacts, overlooking long-term sustainability and health outcomes. Lastly, variations in consumer preferences and behaviours were not accounted for, which can significantly influence market demand and the economic viability of food products. While sensitivity and uncertainty analyses are critical for assessing the robustness of LCA results, the focus of this study is on comparative insights rather than extensive scenario testing. Key assumptions and data sources were carefully selected to minimize variability, ensuring the reliability of the findings. Future research could further validate and strengthen the robustness of the results.

**4. Conclusions**

This study investigated the transition from the commercial mass unit to the nutritional functional unit (n-FU) and its application to burger patties. The analysis revealed the environmental impacts associated with the nutritional profile of food, marking a significant step towards a more comprehensive life cycle assessment (LCA) of meals and dietary patterns. The results highlight the substantial impact of food choices on both human health and the environment, reinforcing the need for integrating economic considerations into the analysis.



**Fig. 7.** Comparative analysis of environmental and economic metrics for burger patties.

By introducing an economic functional unit (e-FU), the analysis provides insights into the cost per nutritional metric, offering a nuanced understanding of the economic viability of environmentally friendly food options. This approach not only enhances consumer awareness of the economic implications of their dietary choices but also informs producers and policymakers about the economic feasibility of transitioning toward more sustainable food systems.

A deeper understanding of additional factors is crucial; satiety and marginal health effects of food intake are complex mechanisms with significant variation between individuals and populations. This n-LCA approach identifies gaps in the nutritional content of similar foods, potentially enabling informed food choices and mitigating some of the negative environmental impacts associated with food production.

The study's identification of meat-based burger patties as having a higher environmental impact and affordability emphasizes the need for refining future research methodologies. Investigating the origins and production systems of meat, including breed, feed ingredients (including water usage), rearing environment, and slaughter age which could significantly influence both environmental and nutritional assessments. Furthermore, exploring strategies like integrating renewable energy across the meat production chain offers promising avenues for future investigation.

Future research stands to enhance the methodology by integrating dietary profiling into n-LCA, allowing for the assessment of dietary and consumption patterns among specific populations. Additionally, examining variations in nutrient content throughout the food chain considering factors such as storage conditions, transport methods, and cooking techniques would yield a more comprehensive understanding of overall nutrient impact and economic viability. Ultimately, this comprehensive approach will guide consumers toward more sustainable and health-conscious food choices while highlighting the economic implications of their dietary decisions.

#### CRediT authorship contribution statement

**Abhishek Dattu Narote:** Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Andrea Casson:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Valentina Giovenzana:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Alessia Pampuri:** Writing – review & editing, Visualization, Resources. **Alessio Tugnolo:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Roberto Beghi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Riccardo Guidetti:** Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

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#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafr.2025.101820>.

#### Data availability

Data will be made available on request.

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