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Life Cycle Analysis of Two Menus: Animal Protein and Plant Protein

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Abstract

Food production has significant environmental impacts, particularly those associated with animal-based products. One often overlooked aspect is the contribution of waste generated during food preparation and handling. The objective of this study was to evaluate and compare the environmental performance of two menus, one animal-based protein and the other on predominantly plant-based protein. The assessment included ingredient production, transportation, food preparation, and waste management. The functional unit was defined as "serving one meal to a student, consisting of a three-course menu". The dataset corresponding to the inputs and outputs of each system was obtained from the Ecoinvent database (version 3.10), implemented in SimaPro v10.3.0.4. Impact categories were assessed using the ReCiPe Midpoint method. A total of 18 impact categories were evaluated, of which four were analyzed in greater detail. The results show that, for the animal-based menu, ecotoxicity is concentrated in a single dominant process—intensive pig production—whereas, for the plant-based menu, it is distributed across multiple secondary processes, primarily municipal solid waste management and industrial processing. Similar results were observed for global warming. Under the evaluated conditions, the assessment revealed that the plant-based menu had a higher environmental impact than the animal-based menu. Because this study included waste management and packaging, the environmental impact of the plant-based menu increased significantly.

Keywords: sustainable and healthy diets; environmental impacts; carbon footprint; waste management; packaging

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1. Introduction

Agri-food systems, which encompass activities ranging from food production, processing, preservation, and storage to distribution and commercialization, account for a significant share of the environmental impacts affecting the planet [1,2]. The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for approximately 22% of global net greenhouse gas (GHG) emissions [3,4]. These emissions arise from multiple sources, including deforestation processes; carbon dioxide (CO_2) associated with increased use of resources such as water, land, and energy; methane (CH_4) produced by the digestive systems of ruminants; and nitrous oxide (N_2O) generated from fertilizers and livestock effluents [3–5].

The livestock industry generates a significant carbon footprint due to methane emissions from ruminant animals, as well as its high demand for water, land, and energy resources [4,5]. In addition, wastewater from livestock production systems and farms (swine, poultry, and aquaculture) contains organic residues, heavy metals, pathogenic bacteria, and parasites, posing potential risks to both the environment and human health [6–9]. The production of synthetic nitrogen and phosphorus fertilizers generates atmospheric pollutants and greenhouse gas (GHG) emissions [10]. Similarly, the excessive use of these substances in agricultural fields is responsible for approximately 78% of global eutrophication in freshwater and marine ecosystems, contaminates aquifers with soluble salts, agrochemical residues, and nitrogen, and alters soil properties through interactions with their components [10–15].

The widespread use of pesticides, such as organochlorine compounds (dichlorodiphenyltrichloroethane (DDT) and endrin) and glyphosate, significantly affects air, water, and soil quality, as well as terrestrial and marine biodiversity. As these substances accumulate along the food chain, they increase health risks, including acute poisoning, cancer, and neurological disorders [12–15].

The conversion of forests, grasslands, and wetlands into grazing areas, croplands (e.g., sorghum, maize, quinoa, agave), or industrial plantations (e.g., oil palm, avocado) alters soil quality due to the application of fertilizers and pesticides, affects biodiversity and landscape integrity, and increases water demand, among other impacts [16–19]. Overgrazing and continuous trampling associated with extensive livestock production act as pressure factors that accelerate soil degradation and the loss of vegetation cover and biodiversity [16,20–22], land-use conversion for agriculture and land degradation remain the leading drivers of global deforestation, accounting for 70–80% of total forest loss.

Another significant source of pollution in agri-food systems arises from packaging materials used for the storage, preservation, and transportation of food. These materials are typically made from a variety of substances, including plastic, glass, metal, paper, cardboard, and multilayer materials. Beyond the impacts associated with their production cycles, these packaging materials become waste after use. Each year, more than two billion tonnes of municipal solid waste (MSW) are generated worldwide, of which only 62% is managed through recycling, energy recovery, or disposal in sanitary landfills [23,24]. Waste management practices vary significantly across countries. High-income countries tend to implement material and energy recovery strategies, including recycling, anaerobic digestion, composting, and incineration; upper-middle-income countries commonly dispose of waste in sanitary landfills; and low-income countries often have limited waste treatment infrastructure, leading to disposal through open burning or dumping in open areas, waterways, and ravines [23,24]. Inadequate waste management contributes to water, air, and soil pollution, biodiversity loss, climate change, and increased incidence of diseases [4,25–30].

Food preparation can also impact air quality. Several studies have shown that cooking with fuels—particularly solid fuels such as firewood, charcoal, and biomass—produces emissions with adverse health effects, including respiratory, cardiovascular, and neurological diseases, as well as premature mortality [31]. During combustion, various pollutants are released, including particulate matter, volatile organic compounds [32], black carbon, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2) [33], 2003), and polycyclic aromatic hydrocarbons. Furthermore, there is evidence that cooking practices—particularly at high temperatures and using inappropriate fuels and oils—constitute a significant source of indoor air pollution. Such exposure is associated with adverse health effects, including respiratory and cardiovascular diseases, as well as long-term cancer risk, representing a significant public health concern [34,35].

Assessing the environmental impacts of an entire agri-food system is complex because it requires considering all processes involved. One of the most comprehensive tools for this purpose is Life Cycle Assessment (LCA), which estimates the potential environmental impacts of products or services using a cradle-to-grave approach. By quantifying material and energy inputs, as well as emissions and waste generated throughout the life cycle, LCA helps identify the stages responsible for the greatest environmental burdens and supports the development of improvement strategies [36–38].

Previous studies have applied LCA to compare the environmental performance of animal- and plant-based protein systems. Costa-Deprá et al. [39] found that plant proteins and poultry generally showed better environmental performance than beef and pork. Dorca-Preda et al. [40] reported that feed production was the main contributor to toxicity impacts in pig production systems, largely driven by pesticide use and heavy metals in manure. Nijdam et al. [41], through an analysis of 52 LCA studies, concluded that environmental footprints are strongly influenced by production systems, with pork and poultry showing more homogeneous results than beef and seafood.

Studies evaluating prepared meals have also highlighted the importance of ingredient production and food processing stages. Hansen et al. [42] found that ready-to-eat meals had higher energy use and greenhouse gas emissions than meals prepared from fresh or semi-prepared ingredients, with meat production being the main contributor. Similarly, Takacs et al. [43] reported that meat-based meals had substantially greater environmental impacts than vegan alternatives, while whole-food vegan meals consistently showed the lowest impacts across categories such as global warming, eutrophication, and acidification.

This article presents the results of a project conducted at Universidad Autónoma Metropolitana, Azcapotzalco Unit (UAM-A), in Mexico City, aimed at raising awareness within the university community about the environmental impacts associated with food production, preparation, and waste management. To evaluate a real-world scenario, two menus offered in the university cafeteria were selected: one animal-based and one predominantly plant-based. The purpose of the study was not to compare the nutritional equivalence of the menus, but rather to assess the environmental impacts associated with the actual meals served daily and the management of the waste generated.

The objective of this study was to evaluate and compare the environmental performance of these two cafeteria menus using Life Cycle Assessment (LCA), considering ingredient production, transportation, food preparation, and waste management, in order to identify the potential environmental impacts associated with each menu.

2. Materials and Methods

The methodology applied in this study was Life Cycle Assessment, conducted in accordance with ISO 14040:2006 and ISO 14044:2006 standards [36,37]. LCA comprises four methodological phases: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results [36,37].

2.1. Phase 1-Goal and Scope Definition

The goal definition included the processes evaluated for each menu: ingredient production, transportation, food preparation, and management of the solid waste generated. In accordance with the LCA objective, the functional unit and system boundaries were established for each menu. Reference flows were calculated based on the two evaluated menus, considering portions intended for a single consumer.

2.2. Phase 2. Life Cycle Inventory (LCI) Analysis

For the development of the Life Cycle Inventory (LCI), information related to ingredient production, transportation, reception, preparation, cooking, and waste management stages was collected from multiple sources. Data on food reception and preparation activities were obtained from the university cafeteria staff, which serves approximately 1800 three-course meals during lunchtime. Information included recipes, ingredient types and quantities, technical and energy specifications of the equipment used, and time-and-motion data associated with each operation. Equipment energy consumption was estimated based on technical specifications and process duration measurements.

To characterize transportation processes, suppliers were interviewed to identify the origin of ingredients and transportation distances to the UAM-A facilities. Combustion-related and greenhouse gas emissions were estimated using emission factors for electricity and LP gas consumption [44].

Packaging materials accumulated during the reception stage were quantified and characterized, while organic waste generated during food preparation was weighed. For the treatment and final disposal stage, it was assumed that all waste generated, both organic and inorganic, was sent to sanitary landfill disposal without prior separation, reflecting common waste management practices in Mexico [23].

Upstream processes associated with ingredient production were modeled using secondary data from the Ecoinvent database (version 3.10), implemented in SimaPro v10.3.0.4 [45]. Infrastructure construction, manufacturing of kitchen equipment and utensils, and washing activities (inputs, utensils, and tableware) were excluded because they were outside the system boundaries.

The dataset corresponding to the inputs and outputs of each system was obtained from the Ecoinvent database (version 3.10) [45].

2.3. Phase 3. Life Cycle Impact Assessment (LCA)

Based on the environmental issues of interest, the ReCiPe Midpoint method (hierarchical perspective) was selected [38]. In this study, 18 impact categories were evaluated: Global warming, Stratospheric ozone depletion, Ionizing radiation, Ozone formation (Human health), Fine particulate matter formation, Ozone formation (Terrestrial ecosystems), Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity, and Water consumption. Impact calculations were performed using SimaPro v10.3.0.4 [45]. Four environmentally relevant categories were selected for more detailed analysis.

In accordance with ISO 14040 and ISO 14044 standards [36,37], the impact assessment phase included the mandatory elements of classification and characterization, together with the optional normalization step.

2.4. Phase 4. Interpretation

In Phase 4, the results of the inventory and impact assessment phases were interpreted according to the objectives of the LCA [36,37].

3. Results and Discussion

3.1. Phase 1-Goal and Scope Definition

The objective of this study was to evaluate and compare the environmental performance of two menus offered in a university cafeteria—one animal-based and the other predominantly plant-based—using LCA, considering ingredient production, transportation, food preparation, and waste management.

The function of the analyzed system is to provide a food service. Based on this, the functional unit was defined as: "serving one meal to a student in a university cafeteria, consisting of a three-course menu." The reference flows corresponded to the two evaluated menus, with portions intended for a single consumer.

The stages considered were: (i) ingredient production; (ii) transportation of ingredients from supply sites to the university cafeteria; (iii) ingredient reception and storage; (iv) food preparation, including cooking and reheating operations with associated energy consumption; and (v) management of the generated solid waste. Figure 1 presents the process flow diagram of the stages included in the analysis.

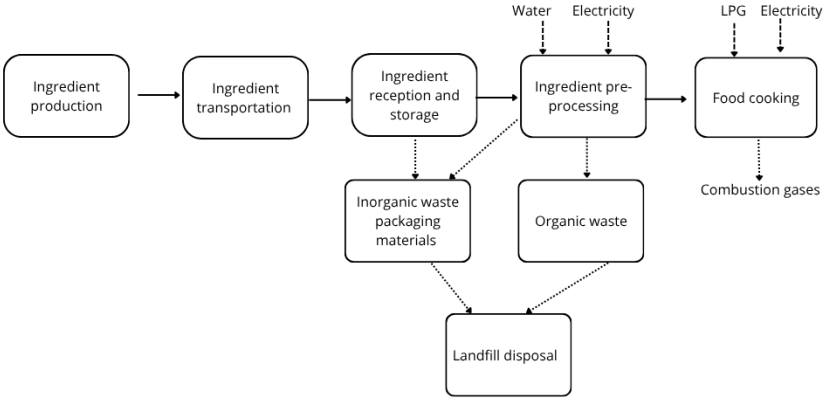


Figure 1. Process flow diagram of the university cafeteria system considered in the life cycle assessment.

The system boundaries for both menus included the input and output flows of materials and energy associated with operations carried out during the production, transportation and reception of ingredients, as well as the food preparation and cooking stages. In addition, waste treatment and final disposal scenarios were included (Figure 1).

3.2. Phase 2. Life Cycle Inventory (LCI) Analysis

The selected menus are presented in Table 1.

Table 1. Animal-based protein menu (Menu 1) and predominantly plant-based protein menu (Menu 2).

Menu 1: Animal-Based Protein	Menu 2: Plant-Based Protein
Pasta soup	Yellow rice
Sweet and sour pork	Mexican-style zucchini
Mashed potatoes	Lentils

Table 2 presents the material and energy requirements for the animal-based and plant-based menus. Input and output data for both menus were quantified according to the defined functional unit and reference flows. In addition, mass and energy balances were performed for each unit process.

Table 2. Requirements for the animal-based protein menu and the predominantly plant-based protein menu (calculated per functional unit).

Animal-Based Protein Menu			**Predominantly Plant-Based Protein Menu**		
Dish 1: Sweet and sour pork			**Dish 1: Mexican-style zucchini**		
Ingredients	**Unit**	**Amount**	***Ingredients***	**Unit**	**Amount**
Pork	g	137.22	Oil	g	1.53
Orange juice	g	13.73	Zucchini	g	122.22

Table 2. *Cont.*

Animal-Based Protein Menu			**Predominantly Plant-Based Protein Menu**		
Ketchup	g	33.33	Onion	g	16.67
Soy sauce	g	3.11	Chicken bouillon	g	1.67
Worcestershire sauce	g	4.36	Canned corn	g	10.83
Seasoning sauce	g	3.56	Tomato	g	83.33
			Diced cheese	g	44.44
			Epazote	g	3.33
System requirements	**Unit**	**Amount**	***System requirements***	**Unit**	**Amount**
LPG *	mg	8.52	LPG	mg	7.85
Electricity	Wh	6.33	Electricity	Wh	7.00
Transport	kg·km	0.74	Transport	kg·km	3.43
System outputs			***System outputs***		
Air emissions	**Unit**	**Amount**	**Air emissions**	**Unit**	**Amount**
Particulate matter	µg	6.33	Particulate matter	µg	5.83
Sulfur dioxide (SO_2)	mg	7.31	Sulfur dioxide (SO_2)	mg	6.73
Carbon monoxide (CO)	mg	13.42	Carbon monoxide (CO)	mg	12.36
Nitrogen oxides (NO_x)	mg	8.04	Nitrogen oxides (NO_x)	mg	7.41
Carbon dioxide (CO_2)	g	23.91	Carbon dioxide (CO_2)	g	22.03
Methane (CH_4)	g	1.73	Methane (CH_4)	g	1.59
Hydrocarbons	g	25.07	Hydrocarbons	g	23.10
Solid waste generation			***Solid waste generation***		
Waste type	**Unit**	**Amount**	**Waste type**	**Unit**	**Amount**
PE ** bag (pork)	mg	159.44	PET container (oil)	mg	83.33
PE bag (ketchup)	g	1.00	PP **** sack (onion)	mg	19.44
PET *** container (soy sauce)	mg	555.56	PET bottle (chicken bouillon)	mg	75.83
Multilayer packaging (orange juice)	mg	533.33	Aluminum cans (corn)	mg	555.56
Glass bottle (Worcestershire sauce)	g	2.71	PE bag (cheese)	mg	22.22
Glass bottle (Maggi sauce)	g	2.60	Organic waste (zucchini)	g	2.44
			Organic waste (onion)	g	1.67
			Organic waste (tomato)	g	4.17
			Organic waste (epazote)	mg	3.33
Dish 2: Pasta soup			**Dish 2: Yellow rice**		
Ingredients	**Unit**	**Amount**	***Ingredients***	**Unit**	**Amount**
Oil	g	1.53	Oil	g	1.53
Onion	g	5.56	Onion	g	5.56
Chicken bouillon	g	1.67	Chicken bouillon	g	1.67
Tomato	g	55.56	Rice	g	27.78
Pasta	g	22.22	Water	g	66.67
Water	g	111.11	Turmeric	g	0.28
System requirements	**Unit**	**Amount**	***System requirements***	**Unit**	**Amount**
LPG	mg	21.25	LPG	mg	5.43
Electricity	Wh	14.14	Transport	kg·km	0.05
Transport	kg·km	0.594			
System outputs			***System outputs***		
Air emissions	**Unit**	**Amount**	**Air emissions**	**Unit**	**Amount**
Particulate matter	µg	15.79	Particulate matter	µg	4.04
Sulfur dioxide (SO_2)	mg	18.23	Sulfur dioxide (SO_2)	mg	4.66
Carbon monoxide (CO)	mg	33.47	Carbon monoxide (CO)	mg	8.55
Nitrogen oxides (NO_x)	mg	20.05	Nitrogen oxides (NO_x)	mg	5.12
Carbon dioxide (CO_2)	g	59.63	Carbon dioxide (CO_2)	g	15.24
Methane (CH_4)	g	4.31	Methane (CH_4)	g	1.10
Hydrocarbons	g	62.52	Hydrocarbons	g	15.98
Solid waste generation			***Solid waste generation***		
Waste type	**Unit**	**Amount**	**Waste type**	**Unit**	**Amount**
PET container (oil)	mg	83.33	PET container (oil)	mg	83.33
PP sack (onion)	mg	6.67	PP sack (onion)	mg	6.50
PET container (chicken bouillon)	mg	75.83	PET container (chicken bouillon)	mg	75.83

Table 2. *Cont.*

Animal-Based Protein Menu			**Predominantly Plant-Based Protein Menu**		
PE bag (pasta)	mg	83.30	PP sack (rice)	mg	44.44
Organic waste (tomato)	g	2.78	PE bag (turmeric)	mg	5.56
Organic waste (onion)	mg	555.55	Organic waste (onion)	mg	555.55
Dish 3: Mashed potatoes			**Dish 3: Lentils**		
Ingredients	**Unit**	**Amount**	***Ingredients***	**Unit**	**Amount**
Chicken bouillon	g	1.67	Oil	g	1.53
Potato flakes	g	22.22	Onion	g	5.56
Milk	g	17.17	Chicken bouillon	g	1.67
Butter	g	3.33	Lentils	g	27.78
Parsley	g	1.67	Tomato	g	55.56
			Bacon	g	11.11
			Water	g	111.11
System requirements	**Unit**	**Amount**	***System requirements***	**Unit**	**Amount**
LPG	mg	0.83	LPG	mg	21.25
Transport	kg·km	0.10	Electricity	kg·km	0.15
			Transport	Wh	0.37
System outputs			***System outputs***		
Air emissions	**Unit**	**Amount**	**Air emissions**	**Unit**	**Amount**
Particulate matter	µg	0.61	Particulate matter	µg	15.79
Sulfur dioxide (SO_2)	mg	0.71	Sulfur dioxide (SO_2)	mg	18.23
Carbon monoxide (CO)	mg	1.30	Carbon monoxide (CO)	mg	33.47
Nitrogen oxides (NO_x)	mg	0.78	Nitrogen oxides (NO_x)	mg	20.05
Carbon dioxide (CO_2)	g	2.32	Carbon dioxide (CO_2)	g	59.63
Methane (CH_4)	g	0.17	Methane (CH_4)	g	4.31
Hydrocarbons	g	2.43	Hydrocarbons	g	62.52
Solid waste generation			***Solid waste generation***		
Waste type	**Unit**	**Amount**	**Waste type**	**Unit**	**Amount**
PET bottle (chicken bouillon)	mg	75.83	PET container (chicken bouillon)	mg	75.83
Kraft paper sack (potato flakes)	mg	177.78	PET container (oil)	mg	83.33
Aluminum foil (butter)	mg	216.67	PP sack (onion)	mg	6.67
Multilayer packaging (milk)	mg	602.78	PP sack (lentils)	mg	44.44
Organic waste (parsley)	mg	166.67	PE bag (bacon)	mg	5.56
			Organic waste (onion)	mg	555.55
			Organic waste (tomato)	g	2.78

* LPG: Liquefied Petroleum Gas; ** PE: Polyethylene; *** PET: Polyethylene Terephthalate; **** PP: Polypropylene.

As shown in Table 2, the plant-based protein menu was not strictly vegetarian, as it included cheese in the zucchini dish and bacon in the lentil dish. However, the original recipes were retained to reflect the actual meals served in the cafeteria.

3.3. Phase 3. Life Cycle Impact Assessment (LCA)

The results of the calculation of the 18 impact categories of the ReCiPe midpoint method for the animal-based protein menu are presented in Table 3 and Figure 2.

Table 3. Life cycle impact assessment results for the animal-based protein menu.

Impact Category	**Unit**	**Soup**	**Sweet and Sour Pork**	**Mashed Potatoes**	**Total**
Global warming	kg CO_2 eq	0.2960746	1.2829108	0.1067455	1.6857309
Stratospheric ozone depletion	kg CFC-11 eq	4.965×10^{-7}	3.946×10^{-6}	6.027×10^{-7}	5.045×10^{-6}
Ionizing radiation	kBq Co-60 eq	0.0027907	0.0416301	0.0023714	0.0467922
Ozone formation, Human health	kg NO_x eq	0.0002764	0.0025599	0.0002597	0.0030961
Fine particulate matter formation	kg PM2.5 eq	0.0001833	0.0027752	0.0001883	0.0031469

Table 3. *Cont.*

Impact Category	Unit	Soup	Sweet and Sour Pork	Mashed Potatoes	Total
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.0002843	0.0026316	0.0002649	0.0031808
Terrestrial acidification	kg SO_2 eq	0.0006666	0.0107508	0.0008664	0.0122840
Freshwater eutrophication	kg P eq	5.691×10^{-5}	0.0004099	5.184×10^{-5}	0.0005186
Marine eutrophication	kg N eq	9.688×10^{-5}	0.0010661	0.0001450	0.0013081
Terrestrial ecotoxicity	kg 1,4-DCB eq	0.3423068	3.6107844	0.5060382	4.4591295
Freshwater ecotoxicity	kg 1,4-DCB eq	0.0031602	0.0411653	0.0053144	0.0496399
Marine ecotoxicity	kg 1,4-DCB eq	0.0041530	0.0520185	0.0054506	0.0616222
Human carcinogenic toxicity	kg 1,4-DCB eq	0.0064791	0.1258065	0.0043304	0.1366161
Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.0948698	0.7106068	0.1256630	0.9311396
Land use	m^2a crop eq	0.0956005	0.6879743	0.2962580	1.0798329
Mineral resource scarcity	kg Cu eq	0.0004084	0.0065863	0.0003962	0.0073911
Fossil resource scarcity	kg oil eq	0.0427869	0.1789489	0.0156806	0.2374164
Water consumption	m^3	0.0093280	0.0410263	0.0082729	0.0586273

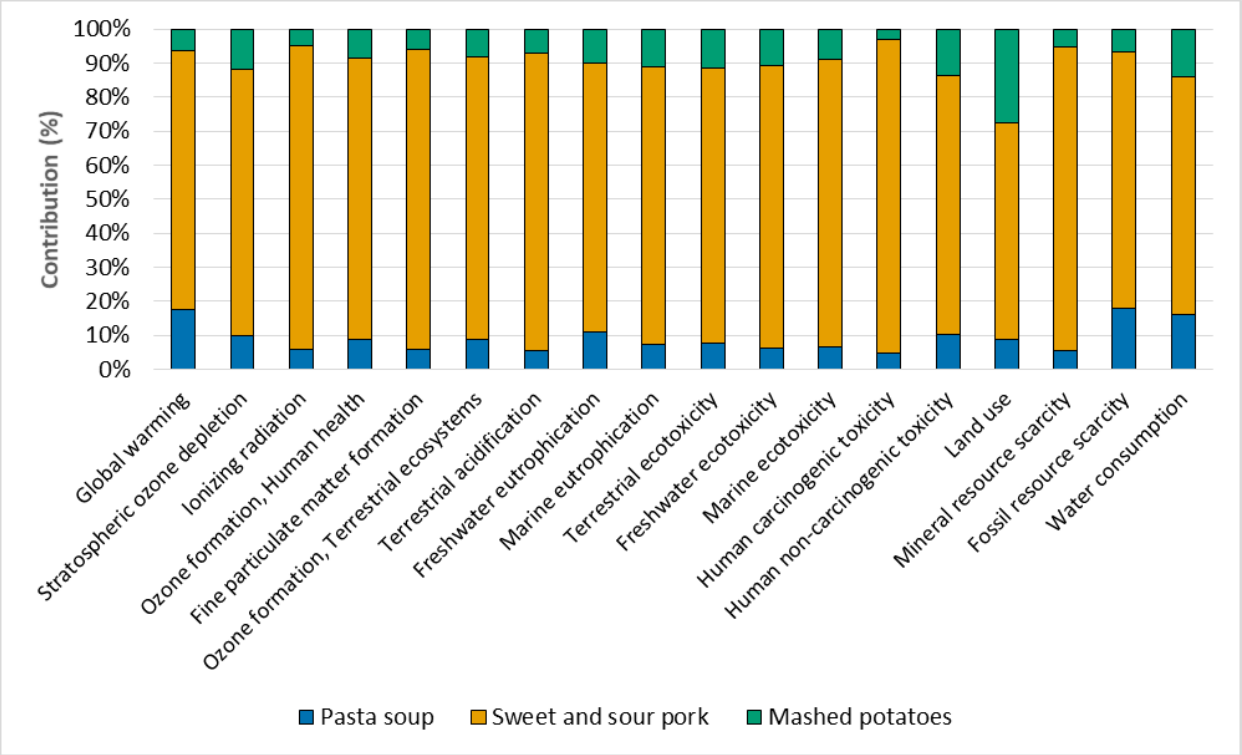


Figure 2. Relative contribution (%) of each dish to ReCiPe 2016 midpoint impact categories for the animal-based protein menu.

As shown in Figure 2, for the animal-based menu, the Sweet and Sour Pork dish accounted for the largest contribution across most of the 18 impact categories.

The results of the calculation of the 18 impact categories of the ReCiPe midpoint method for the plant-based protein menu are presented in Table 4 and Figure 3.

As shown in Figure 3, for the plant-based menu, the Mexican-style Zucchini and Lentils dishes accounted for the largest contributions across most of the 18 impact categories.

The comparative assessment of environmental impacts between the animal-based protein menu and the plant-based protein menu is presented in Table 5 and Figure 4.

Table 4. Life cycle impact assessment results for the predominantly plant-based protein menu.

Impact Category	Unit	Rice	Zucchini	Lentils	Total
Global warming	kg CO_2 eq	0.7596994	1.4092254	1.7272965	3.8962213
Stratospheric ozone depletion	kg CFC11 eq	1.878×10^{-6}	4.952×10^{-6}	3.855×10^{-6}	1.068×10^{-5}
Ionizing radiation	kBq Co-60 eq	0.0451624	0.0476989	0.0970192	0.1898806
Ozone formation, Human health	kg NO_x eq	0.0013610	0.0024199	0.0030010	0.0067820
Fine particulate matter formation	kg PM2.5 eq	0.0009276	0.0017200	0.0021087	0.0047564
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.0014149	0.0024919	0.0031205	0.0070274
Terrestrial acidification	kg SO_2 eq	0.0020634	0.0058224	0.0048878	0.0127737
Freshwater eutrophication	kg P eq	0.0004593	0.0010077	0.0010013	0.0024683
Marine eutrophication	kg N eq	0.0002051	0.0009075	0.0003426	0.0014553
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.6943001	3.5603748	3.8598857	9.1145606
Freshwater ecotoxicity	kg 1,4-DCB eq	0.0658568	0.1567706	0.1389134	0.3615409
Marine ecotoxicity	kg 1,4-DCB eq	0.0864581	0.2053304	0.1827438	0.4745324
Human carcinogenic toxicity	kg 1,4-DCB eq	0.0302616	0.0538496	0.0759598	0.1600711
Human non-carcinogenic toxicity	kg 1,4-DCB eq	1.4642331	3.4084512	3.0924320	7.9651163
Land use	m^2a crop eq	0.0779019	2.6306549	0.3004704	3.0090272
Mineral resource scarcity	kg Cu eq	0.0017024	0.0035340	0.0042196	0.0094562
Fossil resource scarcity	kg oil eq	0.2855609	0.2923062	0.6186122	1.1964794
Water consumption	m^3	0.0344625	0.0261844	0.0206757	0.0813226

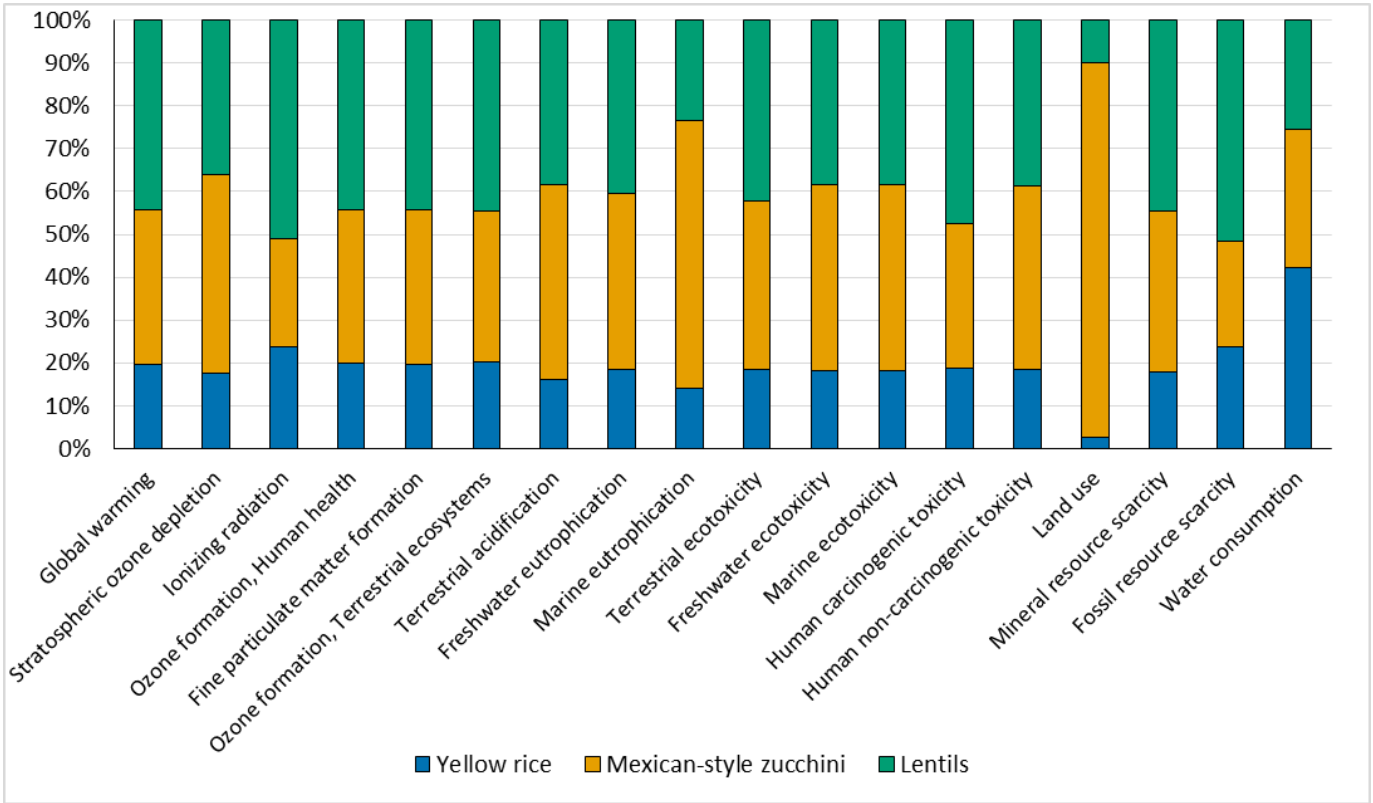


Figure 3. Relative contribution (%) of each dish to ReCiPe 2016 midpoint impact categories for the plant-based protein menu.

Table 5. Percentage difference in impact categories between the two menus.

Impact Category	Animal-Based Menu	Predominantly Plant-Based Menu	Relative Difference (%)
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.93114	7.96512	755.40%
Marine ecotoxicity (kg 1,4-DCB eq)	0.06162	0.47453	670.10%
Freshwater ecotoxicity (kg 1,4-DCB eq)	0.04964	0.36154	628.30%
Fossil resource scarcity (kg oil eq)	0.23742	1.19648	403.96%
Freshwater eutrophication (kg P eq)	0.00051	0.00246	375.90%
Ionizing radiation (kBq Co-60 eq)	0.04679	0.18988	305.80%
Land use (m^2a crop eq)	1.07983	3.00903	178.66%
Global warming (kg CO_2 eq)	1.68573	3.89622	131.13%
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	0.00318	0.00702	120.92%
Ozone formation, Human health (kg NO_x eq)	0.00309	0.00678	119.06%
Stratospheric ozone depletion (kg CFC11 eq)	0.000005	0.00001	111.80%
Terrestrial ecotoxicity (kg 1,4-DCB eq)	4.45913	9.11456	104.40%
Fine particulate matter formation (kg PM2.5 eq)	0.00314	0.00475	51.15%
Water consumption (m^3)	0.05863	0.08132	38.70%
Mineral resource scarcity (kg Cu eq)	0.00739	0.00945	27.94%
Human carcinogenic toxicity (kg 1,4-DCB eq)	0.13662	0.16007	17.17%
Marine eutrophication (kg N eq)	0.00130	0.00145	11.25%
Terrestrial acidification (kg SO_2 eq)	0.01228	0.01277	3.99%

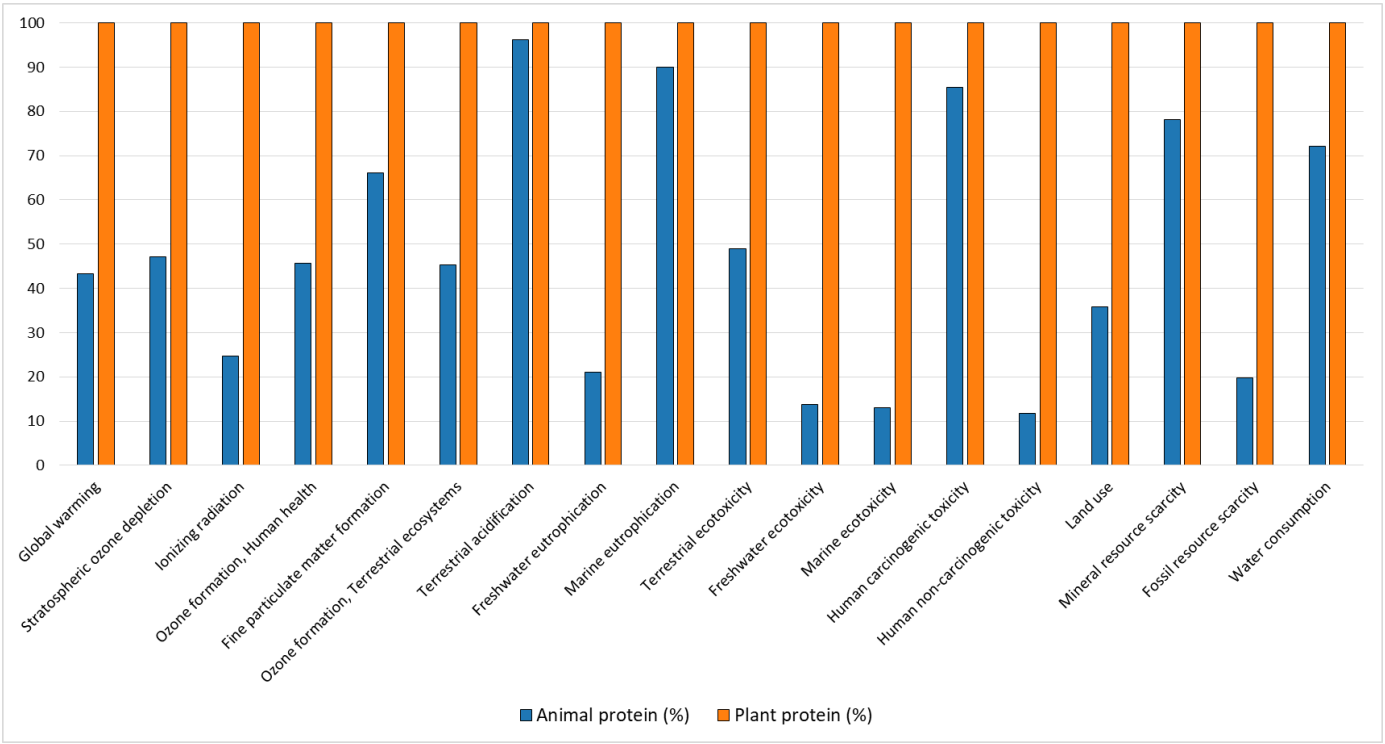


Figure 4. Comparative assessment of environmental impacts between the animal-based protein menu and the plant-based protein menu.

Substantial differences are observed across most of the analyzed categories, with the plant-based menu exhibiting higher environmental impacts in the 18 categories evaluated.

Considering that the most significant differences are observed in the categories of human non-carcinogenic toxicity, marine ecotoxicity and freshwater ecotoxicity, this study focuses on the analysis of these impact categories. In addition, the global warming category is included, as it represents one of the most critical environmental issues worldwide.

3.3.1. Ecotoxicity

In the case of the animal-based menu, ecotoxicity was highly concentrated in a single hotspot: sweet and sour pork dish (Figures 2 and 5).

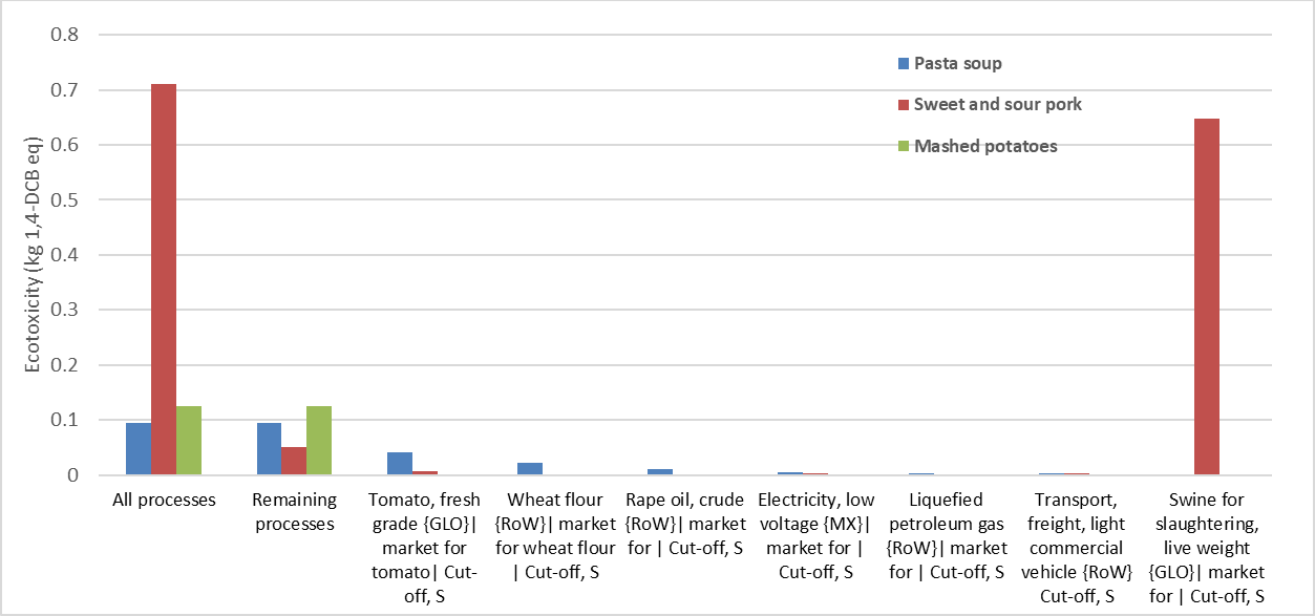


Figure 5. Contribution of processes to ecotoxicity in the animal-based protein menu.

The sweet and sour pork dish contributed 76.3% of human non-carcinogenic toxicity, 82.9% of freshwater ecotoxicity, and 84.4% of marine ecotoxicity of the total impact of the animal-based menu. Within this dish, the process "Swine for slaughtering" was the main contributor across all three subcategories, accounting for 0.647 kg 1,4-DCB eq in human non-carcinogenic toxicity, 0.0497 kg 1,4-DCB eq in marine ecotoxicity and 0.0385 kg 1,4-DCB eq in freshwater ecotoxicity, representing more than 90% of the impact of the sweet and sour pork dish in each case.

For the predominantly plant-based menu, the dominant process across the three analyzed subcategories was municipal solid waste treatment in a sanitary landfill, which accounted for approximately 70–71% of the total impact of the plant-based menu (Figures 3 and 6).

This process contributed 0.96, 2.61, and 1.99 kg 1,4-DCB eq to human non-carcinogenic toxicity for rice, zucchini, and lentils, respectively; 0.0447, 0.1213, and 0.0927 kg 1,4-DCB eq to freshwater ecotoxicity; and 0.0586, 0.1591, and 0.1216 kg 1,4-DCB eq to marine ecotoxicity.

The comparison between the two menus showed that the plant-based menu generated substantially higher impacts for several categories. Human non-carcinogenic toxicity reached 7.97 kg 1,4-DCB eq, compared with 0.93 kg 1,4-DCB eq for the animal-based menu (≈755% higher). Similarly, marine ecotoxicity reached 0.4745 kg 1,4-DCB eq versus 0.0616 kg 1,4-DCB eq (≈670% higher), while freshwater ecotoxicity reached 0.3615 kg 1,4-DCB eq compared with 0.0496 kg 1,4-DCB eq (≈628% higher) (Table 5 and Figure 4).

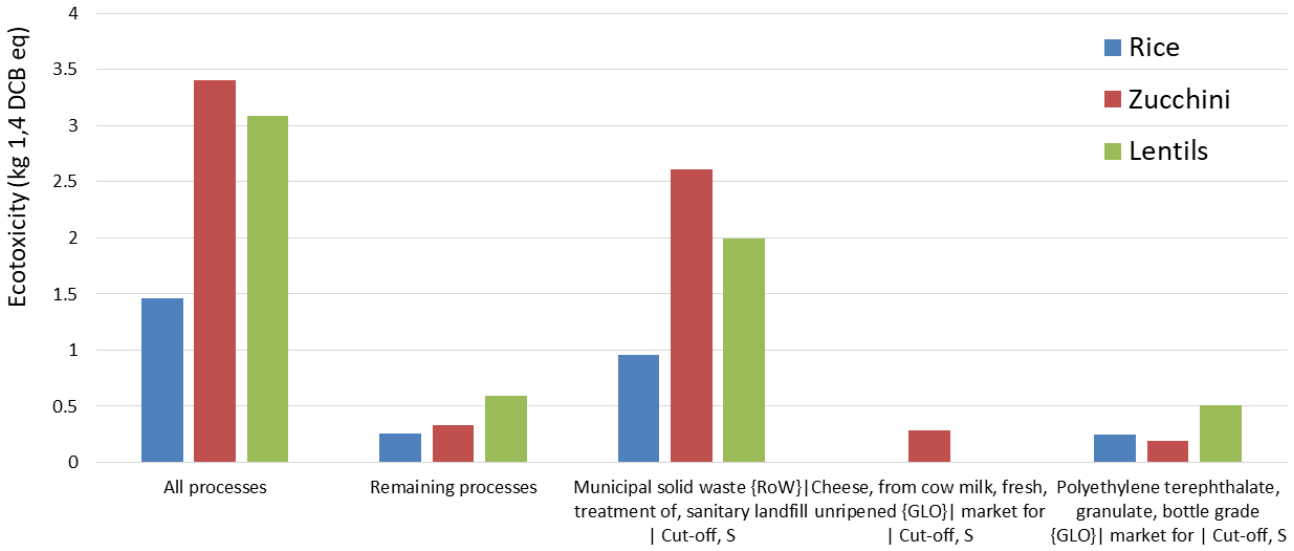


Figure 6. Contribution of processes to ecotoxicity for the predominantly plant-based menu.

3.3.2. Global Warming

For the animal-based menu, most of the climate impact is concentrated in a single dominant process as in the case of ecotoxicity: swine production for slaughtering (swine for slaughtering), which contributes 1.156 kg CO_2 eq, equivalent to 90% of the total impact of the sweet and sour pork dish and 68.6% of the total impact of the animal-based menu (Figures 3 and 7).

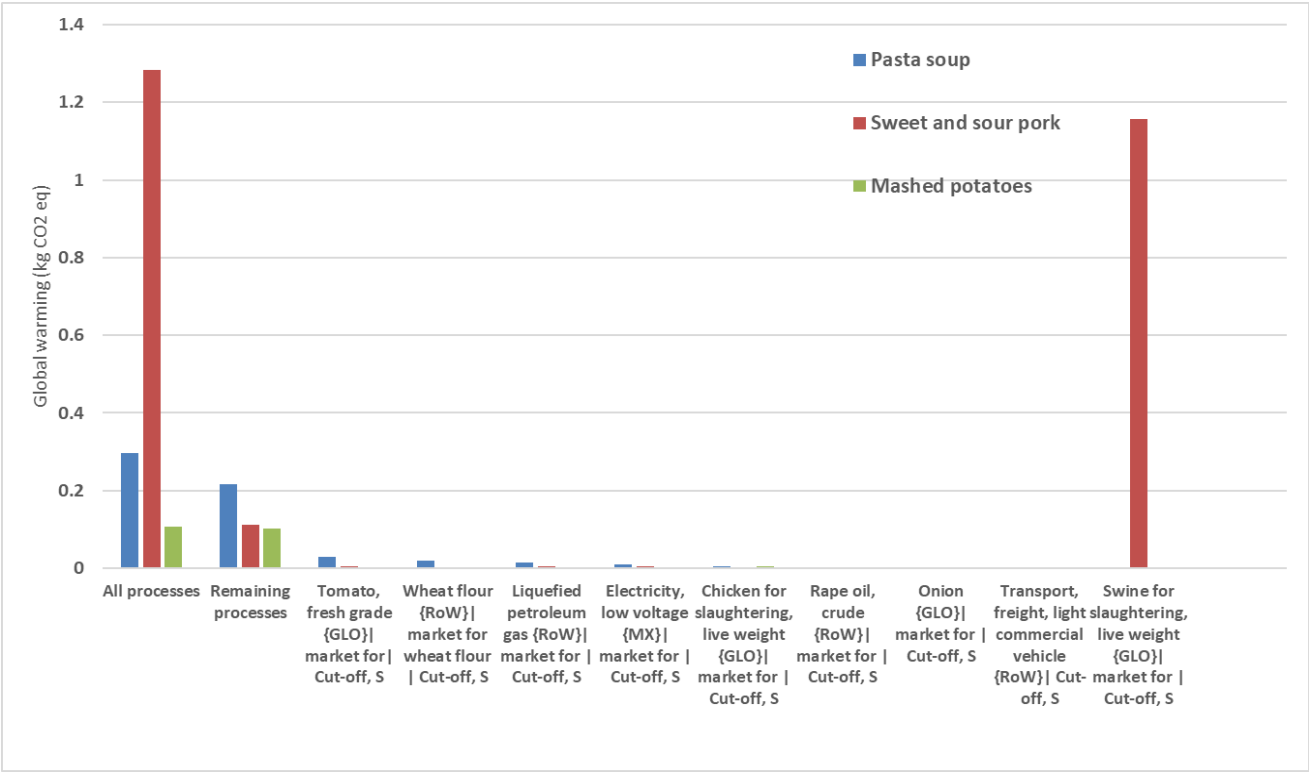


Figure 7. Contribution of processes to global warming for the animal-based menu.

For the plant-based menu, emissions are not concentrated in a single process; rather, as in the case of ecotoxicity, they are distributed among agricultural ingredients and complementary stages (Figures 4 and 8).

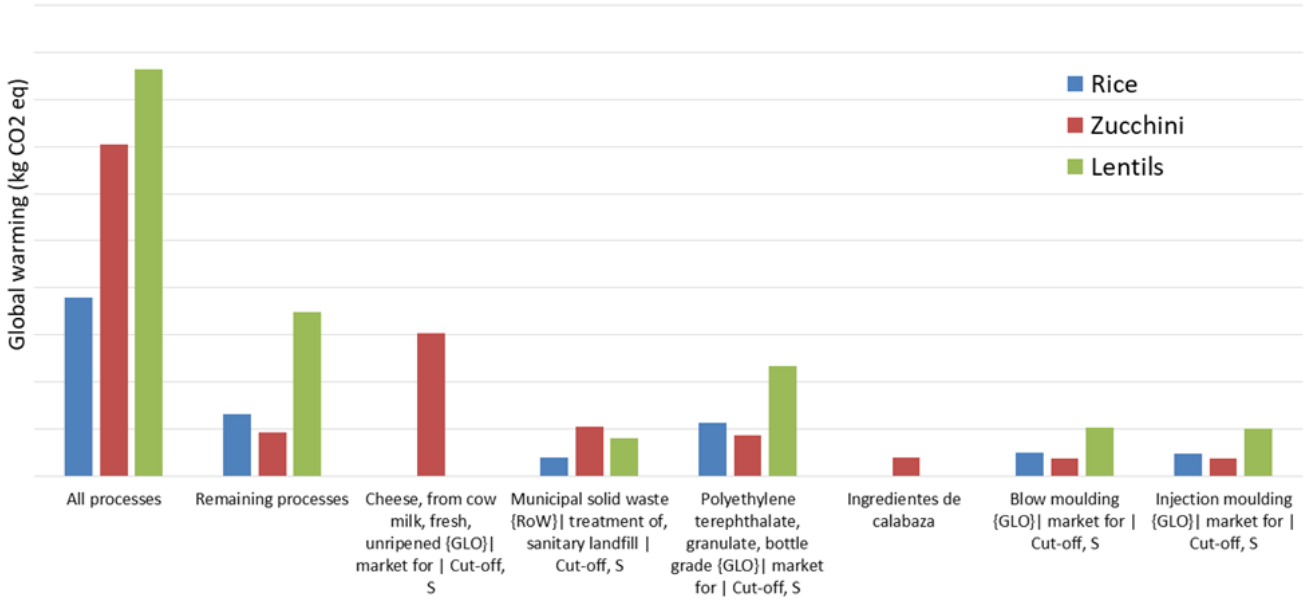


Figure 8. Contribution of processes to global warming for the predominantly plant-based menu.

Lentils, zucchini, and rice exhibit significant environmental burdens, to which additional impacts from packaging, transportation, industrial processing, and final disposal are added. The inclusion of municipal solid waste treatment—covering both organic waste and post-consumer packaging—increased the overall climate burden of the plant-based menu.

The comparison between the two menus showed that, in the global warming category, the plant-based menu recorded 3.896 kg CO_2 eq, whereas the animal-based menu reached 1.686 kg CO_2 eq, representing a 131.1% increase (Table 5 and Figure 4).

3.4. Interpretation

3.4.1. Ecotoxicity

In the case of the animal-based menu, the swine for slaughtering process contributes significantly to ecotoxicity due to energy consumption, the use of cleaning chemicals, and the management of by-products generated during pig production, slaughtering, and processing [46]. Additionally, for animal-based proteins, the slaughterhouse and industrial processing stages may represent a substantial fraction of the total environmental impact in the final stages of the menu [47]. This is further compounded by the indirect burden associated with the production of pig feed, as grains used for animal feeding—such as soy and maize—require intensive use of agrochemicals, thereby increasing the associated ecotoxicity [43].

This behavior confirms that intensive livestock supply chains constitute the main ecotoxic hotspot in meat-based food systems, due to the use of pesticide-treated feed, manure emissions, veterinary residues, and the leaching of nutrients and heavy metals. In this regard, Dorca-Preda et al. [40] report that pesticides such as chlorpyrifos, trifluralin, and glyphosate are responsible for a considerable share of both human toxicity and aquatic ecotoxicity associated with pig production.

In contrast, for the predominantly plant-based menu, the dominant process across the three analyzed subcategories was the post-consumption phase, namely the final disposal of waste generated during menu preparation in sanitary landfills (municipal solid waste, sanitary landfill). At this stage, leachates loaded with heavy metals, persistent organic compounds, and microplastics affect terrestrial, freshwater, and marine ecosystems. Although part of the plastic may be recycled, a significant fraction ultimately undergoes incineration or final disposal, generating additional emissions of greenhouse gases and persistent pollu-

tants [48]. While Costa-Deprá et al. (2022) [39] associate plant-related ecotoxicity primarily with fertilizer and pesticide use, in this study, impacts linked to municipal solid waste clearly predominate.

Another process contributing significant burdens across the three categories was the use of polyethylene terephthalate (PET) as a packaging material for ingredients. In human non-carcinogenic toxicity, PET contributed 0.244 kg 1,4-DCB eq for rice, 0.189 kg 1,4-DCB eq for zucchini, and 0.506 kg 1,4-DCB eq for lentils; in freshwater ecotoxicity, contributions were 0.0103, 0.0080, and 0.0214 kg 1,4-DCB eq; and in marine ecotoxicity, 0.0136, 0.0105, and 0.0282 kg 1,4-DCB eq, respectively. The most influential factors in this category include the release of formaldehyde and cadmium during industrial production processes, as well as operations such as blow moulding, injection moulding, plastic film extrusion, polypropylene granulate production, and nonwoven polypropylene textile manufacturing. Gomes et al. [49] indicate that resin production and bottle manufacturing constitute the main hotspots of PET, particularly in aquatic and terrestrial ecotoxicity. Furthermore, Özer et al. (2025) [48] warn that even energy recovery technologies do not fully eliminate the release of persistent pollutants, while Bartwal et al. [50] highlight that PET production commonly uses antimony as a catalyst (100–300 mg/kg), representing an additional potential source of toxicity if released into the environment.

3.4.2. Global Warming

For the animal-based menu, swine production for slaughtering (swine for slaughtering) again emerges as the dominant process. This confirms that pork-based protein constitutes the main environmental hotspot, due to emissions associated with feed production, livestock management, manure handling, transportation, and industrial processing [46,47]. In contrast, other components of the animal-based menu, such as the soup and mashed potatoes, show considerably lower contributions.

Feed production represents the dominant stage within the pork supply chain, accounting for between 62% and 87.7% of the total global warming impact. These emissions primarily arise from the use of nitrogen fertilizers in the cultivation of grains such as wheat and soy, as well as from fossil fuel consumption in agricultural machinery. In addition, manure management accounts for approximately 24% of on-farm emissions due to the release of CH_4 and N_2O during storage and application.

Energy use on farms for heating and ventilation, as well as in slaughterhouses for refrigeration, also significantly increases emissions when electricity is derived from fossil sources [41]. Transportation also plays a relevant role, particularly when feed ingredients are imported over long distances, potentially accounting for up to 38.3% of the contribution to climate change in certain production systems [47].

For the plant-based menu, emissions are distributed across multiple agricultural ingredients—such as lentils, zucchini, and rice—as well as complementary stages related to packaging use, transportation, industrial processing, and final waste disposal. This result is explained not only by the cumulative burden of plant-based ingredients, particularly lentils (1.727 kg CO_2 eq) and zucchini (1.409 kg CO_2 eq), but also by the contribution of GHG emissions associated with municipal solid waste management, which was explicitly included within the system boundaries of the life cycle assessment. These findings indicate that some plant-based ingredients, especially those requiring more intensive processing, packaging, and end-of-life management, may exhibit relevant climate burdens, as also reported by Kyttä et al. [51].

Municipal solid waste, particularly post-consumer packaging, increases the climate burden through multiple mechanisms [42]. Plastic packaging and non-recyclable materials raise global warming potential, especially when oversized packaging or inefficient logistics

are involved, increasing transport-related emissions [41]. Although in other scenarios incineration with energy recovery can partially offset fossil energy demand, the combustion of fossil-based plastics is not carbon-neutral and may add approximately 0.1 kg CO_2 eq per serving to the total climate burden [42].

3.4.3. Comparative Perspective

The comparative assessment of environmental impacts between the animal-based and predominantly plant-based menus, under the analyzed conditions, revealed substantial differences across most of the analyzed categories, with the plant-based menu exhibiting higher environmental burdens than the animal-based menu: the plant-based menu's impact was 628 to 755% higher across the three ecotoxicity subcategories, and 131.1% higher in the global warming category than animal-based menu.

For the animal-based protein menu, the three ecotoxicity subcategories are concentrated in a single dominant process—swine for slaughtering process. In contrast, those for the plant-based protein menu are distributed across multiple secondary processes, primarily municipal solid waste management, plastic packaging, and industrial processing [39,40,52]. Regarding global warming category, impacts from the animal-based menu are dominated by swine for slaughtering process. Meanwhile, for the plant-based menu, they stem primarily from plastic packaging, the final disposal of food waste, agricultural production and complementary processes.

From a comparative perspective, these results indicate that the environmental impact of the menus depends not just on whether the ingredients are animal or plant-based, but on the interaction of multiple factors across the entire value chain, including primary production, processing, packaging, logistics, and waste management.

These findings contrast with previous studies, such as those by Takács et al. [43], Detzel et al. [53], and Varela-Ortega et al. [54], which report more consistent environmental advantages for plant-based diets.

This discrepancy may be explained by the fact that many previous assessments focus on the primary production stage and do not explicitly incorporate the post-consumption phase. In this analysis, the inclusion of municipal solid waste management and post-consumer packaging substantially altered the overall balance, particularly increasing the environmental burden of the plant-based menu.

From a nutritional perspective, although animal proteins exhibit higher bioavailability of essential amino acids, Kyttä et al. [51] and McAuliffe et al. [55] agree that plant-based proteins can adequately meet nutritional requirements when diets are properly balanced. However, this study shows that their environmental performance depends critically on the type of crop, the production system, and the inclusion of stages often overlooked, such as waste management.

The complexity of these processes can substantially alter the environmental balance between animal-based and plant-based food systems. In this sense, although plant-based foods are generally associated with lower emissions, their environmental advantage may be reduced or even reversed when complex supply chains, high levels of processing, and systems with high waste generation are considered.

4. Conclusions

The objective of this study was to evaluate and compare the environmental performance of two menus offered in a university cafeteria—one animal-based and the other predominantly plant-based—using LCA and considering ingredient production, transportation, food preparation, and waste management. The study assessed real-world conditions through the selection of two menus actually served in the university cafeteria. It is impor-

tant to note that this work did not aim to compare the nutritional equivalence of the menus but rather to evaluate the environmental impacts associated with the daily portions served to students and the management of the waste generated. A key methodological aspect of this study was the explicit inclusion of waste management within the system boundaries of the life cycle assessment.

Analysis of the 18 impact categories using the ReCiPe method showed that, for the animal-based menu, the Sweet and Sour Pork dish contributed the highest impacts compared with Pasta Soup and Mashed Potatoes. In the plant-based menu, Mexican-style Zucchini and Lentils showed the largest contributions across the evaluated impact categories.

The comparative assessment revealed that the plant-based menu exhibited higher environmental impacts across the 18 evaluated categories. For ecotoxicity-related categories, impacts in the animal-based menu were concentrated in swine production, whereas, in the plant-based menu, impacts were distributed among several secondary processes, particularly municipal solid waste management, plastic packaging, and industrial processing.

For global warming, impacts in the animal-based menu were primarily associated with swine production. In contrast, the plant-based menu was influenced mainly by plastic packaging, the final disposal of food waste, agricultural production and complementary processes.

Although previous studies frequently report environmental advantages for plant-based diets, the plant-based menu in this study showed higher impacts in key categories such as ecotoxicity and global warming. These findings were mainly explained by the cumulative contribution of multiple crops, packaging materials, transportation, industrial processing, and final waste disposal.

This study demonstrates that the environmental sustainability of meals depends not only on food origin but also on the full set of processes that compose their life cycle. Therefore, designing sustainable diets requires multicriteria approaches that simultaneously integrate nutritional quality, production efficiency, environmental impact reduction, and optimized waste management.

In light of these findings, expanding the availability of plant-based menus is still recommended. However, lower-impact ingredients should be prioritized, particularly those requiring less packaging or those with greater recovery potential. Additionally, implementing waste separation programs for both staff and consumers would support a more integrated and sustainable management of cafeteria waste.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse Gas
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
CO	Carbon monoxide
NO_x	Nitrogen oxides
SO_2	Sulfur dioxide
MSW	Municipal Solid Waste
LCV	Life Cycle Assessment
UAM-A	Universidad Autónoma Metropolitana, Unidad Azcapotzalco
LPG	Liquefied Petroleum Gas
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
1,4-DCB	1,4-dichlorobenzene

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