

Environmental Affects of Plant-Based Beef Analog Production in 12 Countries and Consumer Response to Plant-Based Meat in China, A Case Study

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Abstract This study employs a multi-regional life cycle assessment (LCA) across 12 countries to quantify and compare environmental impacts of plant-based beef analogue (PBBA) versus conventional beef production. Key drivers of ecological footprints were identified: PBBA reduced greenhouse gas emissions by 80–90% but exhibited critical regional bottlenecks—soybean-driven deforestation in Argentina (contributing >70% to global warming impacts) and coal-dependent processing in China (amplifying fine particulate matter formation by 69%). Significant spatial disparities emerged in resource efficiency: beef production demanded 7.8× more water and 22.9× greater land use than PBBA, with nitrogen/phosphorus runoff from feed cultivation causing freshwater eutrophication (18.8× higher in beef systems). Substitution modelling revealed that replacing 1% of China’s beef consumption annually with PBBA could reduce agricultural emissions by 0.4–0.7%, cumulatively mitigating 12.8 million tons of CO₂ by 2030. However, consumer surveys across 18 Chinese cities identified taste authenticity as the primary adoption barrier (41.5% rejection in culinary hubs; $\beta = -0.53$, $*p < 0.001$), mediated by cultural identity (62%), while economic vulnerability tripled price sensitivity among low-income youth versus older cohorts. The findings underscore that scaling PBBA requires region-specific interventions—addressing supply-chain bottlenecks (e.g., deforestation-free soy sourcing, renewable energy integration) and demand-side cultural adaptation (e.g., recipe reformulation with chefs)—to align planetary health goals with dietary transitions.

Keywords: Consumer behaviour, Food culture, Plant-based beef, Sustainable diets, Life cycle assessment, Dietary transition

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1. Introduction

Sustainable development has been a hot topic around the world since the last century. To comprehensively address development issues in the social, economic, and environmental dimensions from 2015 to 2030 and transition towards a sustainable development path, 17 Sustainable Development Goals (SDGs) were established on the 2015 United Nations Sustainable Development Summit, such as zero hunger (SDG2), good health and well-being (SDG3), responsible consumption and production (SDG12), climate action (SDG13), life below water (SDG14) as well as life on land (SDG15). It is predicted that the global population will grow to more

than 9 billion by 2050, which can not only exhibit huge impacts on the global ecological environment, but can also lead to a substantial increase in demand for food, especially for meat production [1]. The total global meat consumption was 359 million tons in 2022 [2], among which China's total meat consumption was 94.9 million tons (accounting for 26.4% of the global total). However, the issue of unsustainable meat supply is becoming increasingly prominent on account of environmental pollution, resource depletion and health risk. In agricultural production, animal husbandry exerts the most significant effects on the global atmospheric, terrestrial and marine ecologies. Researchers believe that half of the deforestation and CO₂ emissions around the world can be avoided by replacing 20% of global beef consumption. According to the study [3], the global GHG (greenhouse

gas) emissions from food production in 2010 were $17318 \pm 1675 \text{ TgCO}_2\text{eq yr}^{-1}$, while 57% corresponded to the animal food (including livestock feed) and 29% corresponded to plant-based food production. For instance [1], the carbon footprint of plant-based protein-rich alternatives were generally lower than their animal-based counterparts. Specifically, soybean meal-based meat replacers (272 g CO_2eq per 100 g), tofu-based meat substitutes (130 g CO_2eq per 100 g), soy-based milk alternatives (22–51 g CO_2eq per 100 g), and pea-based drinks (61 g CO_2eq per 100 g) exhibited lower carbon footprints compared to chicken breast meat (232–342 g CO_2eq per 100 g) and cow's milk (191–244 g CO_2eq per 100 g). In terms of resource utilization, meat-based food system also requires much more energy, land and water resources than plant-based diet [4]. According to the Global Burden of Diseases Study [5], cardiovascular diseases (CVD) caused 19.8 million deaths globally in 2022, with unhealthy dietary patterns (including excessive consumption of animal-based proteins and saturated fats) identified as a leading behavioral risk factor. Besides, it is reported that 20% of global populations are vegetarians (5%) and flexitarians (15%). Therefore, plant-based food production and consumption have gained global attention for their potential to contribute to multiple SDGs.

As the family of plant protein-based products, plant-based meat analogues are usually made from soybean protein, pea protein and/or wheat protein [6]. The main techniques to produce plant-based meat analogues include extrusion, shear cell, mixing proteins hydrocolloids, freeze structuring, electrospinning and wet spinning, etc [7,8]. On account of the mitigating effects of plant-based meat products on the negative environmental impact brought by the production and consumption of animal meat products as well as their health-promoting effects and nutritional benefits, more and more food companies have begun to develop a series of innovative plant-based meat products during the past decade, like replacements for: tuna [9], bacon (based on soy protein and seitan protein) [10], sausages (mainly based on pea protein) [11], hamburger patty (based on soybean meal and pumpkin seed flour) [12], chicken nuggets (based on soybean, groundnut and cowpea flours) [13], pork belly (mainly based on soy protein isolate) [14], beef [15] and egg (based on mung beans, pumpkin seeds, fungi.) [16] etc. Currently, the well-known domestic plant-based meat brands in the world include Impossible Foods, Beyond Meat, Gardein, Field Roast, Modern Meadow, etc. Among them, Impossible Foods has secured nearly \$700 million in funding [17]. The data from Nielsen Plant-based food association shows global sales revenue of plant-based meat products has reached \$3.3 billion. Moreover, according to the projection of A.T. Kearney, the global sales revenue of plant-based meat analogues is expected to reach \$370 billion by 2035 and account for 23% of the global meat market share.

The impacts of animal and plant-based meat production on the ecological environment have been compared in several studies already. For instance [18], a global economic land use model was utilized to assess the food system-wide impacts of a global dietary shift towards plant-based animal product alternatives. Through scenario analysis using the GLOBIOM model, the study projected

that substituting 50% of global pork, chicken, beef, and milk consumption with plant-based alternatives by 2050 could nearly halt the net reduction of forest and natural land, compared to a baseline scenario without dietary changes. Nevertheless, researchers mainly focused on the effects of substitution of all meat products with plant-based meat products on the global environment. However, current life cycle assessments of PBBA lack granularity in three dimensions. First, multi-regional comparisons to address spatial disparities in ecological impacts (e.g., water scarcity in ZA (Zuid-Afrika) vs. coal dependency in CN (China)). Secondly, integration of consumer behavior dynamics, where price sensitivity and taste preferences disproportionately affect adoption rates in developing economies. Third, simulating policies that support NDC (nationally determined contributions) targets, with a focus on China's feed-corn dependency and urban-rural disparities in consumption. This gap is critical, as prior research [18] overestimates global substitution benefits by 12–18% when ignoring regional energy mixes and land-use trade-offs.

To address these limitations, this study conducts the first multi-regional LCA encompassing 12 countries, combining scenario analysis, Monte Carlo sensitivity testing (50,000 iterations), and consumer surveys across 18 Chinese cities. Three innovations distinguish our work, first, we constructed a policy-driven model to quantify how PBBA substitution interacts with China's coal-to-renewables transition and soybean import policies, revealing that a 1% annual substitution rate could reduce agricultural emissions by 0.4–0.7%—equivalent to 12.8 million tons of CO_2 mitigation by 2030. Then by integrating with behavioral economics and through structural equation modeling (SEM), we identify tiered subsidy mechanisms that could boost PBBA acceptance in low-income regions by 17%, contrasting with taste-centric strategies for urban markets. Based on the above analysis, we formulated through supply chain decoupling, and propose a "zero-deforestation certification" framework for Sino-Brazilian soybean trade, addressing 85% of China's import-related ecological leakage—a solution absent in existing literature.

By bridging these gaps, our research not only advances methodological rigor in environmental management but also provides actionable pathways for China to align dietary transitions with SDG12 (Responsible Consumption) and SDG13 (Climate Action). The findings offer policymakers a toolkit to navigate the trilemma of emission reduction, food security, and social equity in emerging economies.

2. Methods

2.1. Analytical Methods and Data Source

The life cycle assessment (LCA) method was used to evaluate the environmental impact of producing 1 kg of beef and equivalent weight of PBBA in 12 countries, while the countries and corresponding abbreviations are as follows: China - CN, Japan - JA, the United States - US, Canada - CA, Great Britain- GB, Deutschland - DE, Zuid Africa - ZA, Nigeria - NG, Brazil - BR, Argentina - AR,

Australia - AU, New Zealand - NZ. A series of environmental indicators of atmospheric ecology, terrestrial ecology, water ecology and human health among different countries were quantified by the software Simapro 9.0 (Table 1). A substitution model was established to further estimate the benefits for achieving SDGs after a consumption substitution of beef with plant-based analogues.

Table 1. Environmental indicators

Primary index	Secondary index	Unit	Abbreviation
Atmospheric ecology	Global warming 100	kg CO ₂ eq	GW
	Ozone formation	kg NO _x eq	OF
	Fine particulate matter formation	kg PM _{2.5}	FPMF
Terrestrial ecology	Terrestrial ecosystems	kg NO _x eq	TE
	Terrestrial acidification	kg SO ₂ eq	TA
	Terrestrial ecotoxicity	kg 1,4-DCB	TT
	Land use	m ² a crop-eq	LU
Aquatic ecology	Freshwater eutrophication	kg P-eq	FE
	Marine eutrophication	kg N-eq	ME
	Freshwater ecotoxicity	kg 1,4-DCB	FT
	Marine ecotoxicity	kg 1,4-DCB	MT
	Water consumption	m ³	WC

Beef production data derived from the combination of on-site investigations of agricultural enterprises and references, as detailed in 2.2.1. PBBA production data comes from the actual operation process of our research group, details refer to 2.2.2. The data on Chinese consumers' beef consumption comes from the research conducted by the National Health and Health Commission of the People's Republic of China in 2022-2023. The data on PBBA consumption comes from the 2022-2023 market research conducted by Shandong Yuwang Ecological Industrial Co., Ltd (Figure 1).

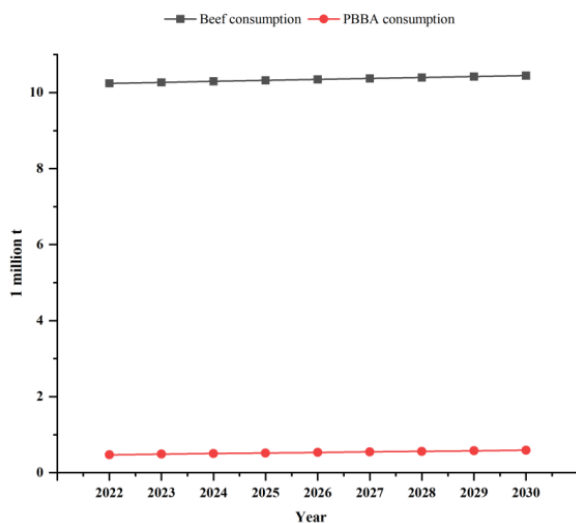


Figure 1. Beef and PBBA consumption from 2022 to 2030 in China. Note: The consumption of beef or PBBA from 2024 to 2030 was predicted value

2.2. Data sources for Beef and PBBA Production

2.2.1. Beef Production

Since different countries employ distinct feeds and feeding methods for cattle breeding and fattening, our study integrated the data from beef cattle farms in Beijing and the feeding methods in previous studies [19,20,21,22], the weight of shelf cattle (300 kg), fattening period (3-4 months), fattening weight (more than 500 kg) and the slaughter rate (48% - 54%) were unified. During the fattening period of beef, concentrate feed and silage feed should be fed reasonably to improve the quality. Roughage was based on various kinds of grass and corn stalks, while each cow was fed an average of 9-10 kg per day. Based on the data from literature and survey [23,24], the feed intake of refined feed for cattle was 3-5 kg/day, including corn (75%), soybean meal (15%), flaxseed meal (5%) and wheat bran (5%). In large-scale culture mode, the consumption of corn, soybean, flaxseed and wheat bran for the production of 1 kg of beef was 2.25-3.75 kg, 0.45-0.75 kg, 0.15-0.56 kg and 0.15-0.25 kg, respectively. The parameters for beef production was summarized in Table 2.

Table 2. Parameters for beef production

Stage	Item	Consumption value/Discharge value	Input index in the model
Breeding stage	Feeding water	540 L/An	2.4 L
	Maize meal	843.75 kg/An	3.75 kg
	Wheat bran	56.25 kg/An	0.25 kg
	Rapeseed meal	126 kg/An	0.56 kg
	Soybean meal	168.75 kg/An	0.75 kg
	Excrement	10 - 14 t/An	62.2 kg
	Urine	7 - 11 t/An	48.9 kg
	Enteric fermentation	1.9 - 4 t CO ₂ e	17.8 kg
Slaughtering and storage stage	Slaughtering equipment	2.5 kWh	
	Storage equipment	0.3 kWh	
	Refrigeration house	180 kWh	1.715 kWh
Transport and storage stage	Home, supermarket refrigerator, etc	(4.67-9.2) * 10 ⁵ kWh	
	Large and medium-sized truck	35.07 L/t/100 km	1*100 kg/km

An: per animal

2.2.2. Production of PBBA

Table 3 showed the process and parameters for the production of PBBA, respectively. First, soybean raw materials were pressed and crushed to obtain soybean meal with 50% protein content. Then the soybean protein concentrate powder with more than 65% protein content was purified and dried by acid method/ethanol method or alkali extraction and acid precipitation method to purify dried protein isolate with more than 90% protein content. Subsequently, soybean protein powder was extruded by high temperature and high pressure spiral mechanical extrusion in accordance with dry texturized vegetable protein or wet high moisture meat analogues to recombine

protein molecules. Ultimately, the tissue structure of samples was formed by cooling expansion at the mold area. Notably, the deep processing processes of PBBA

mainly included soaking, centrifugation, seasoning, mixing, molding, cooking, freezing and packaging, etc.

Table 3. Parameters for the production of plant-based beef analogues

Stage	Item	Consumption value	Input index in the model		
Raw material acquisition	Irrigation water	1000 kg/A	2.5 m ³		
	Soybean seed	3 kg/A	0.56 kg		
	Fertilizers	Urea (As N)	10 kg/A	0.025 kg	
		Phosphatic fertilizer (As P ₂ O ₅)	25 kg/A	0.0625 kg	
		Potash fertilizer (As K ₂ O)	10 kg/A	0.025 kg	
	Pesticides	Pesticide	15 g/A		
		Bactericide	20 - 30 g/A	0.0208 kg	
		Herbicide	30 - 40 g/A		
	Product processing	Protein extraction	Sodium hydroxide	1.23 g/100g Pro	2.315 g
			Hydrochloric acid	0.34 mL/100g Pro	0.64 mL
Energy consumption of machinery		Heating and stirring equipment	(4 - 5) * 10 ⁻² kWh		
		Extrusion equipment	5 * 10 ⁻² kWh		
		Mechanical agitator	1.5 * 10 ⁻² kWh	0.0081 kWh	
Transport and storage	Storage	Refrigeration house	25 kWh		
		Home, supermarket refrigerator, etc	(4.67-9.2) * 10 ⁻² kWh		
	Cold-chain transportation	Large and medium-sized truck	35.07 L/100 km	1*100 kgKm	

A: acre; Pro: protein.

2.3. Evaluation of Consumption Substitution of Beef with Pbba on Alleviating the Negative Environmental Impacts in China

We constructed four scenarios to evaluate the sustainability benefits of substitution of beef with PBBA at different ratios in China as follows. Scenario A: substituting beef with all PBBA consumed in this year in China, scenario B: substituting beef with half of PBBA consumed in this year in China, scenario C: substituting beef with one-third of PBBA consumed in this year in China, scenario D: substituting beef with one-quarter of PBBA consumed in this year in China. Notably, the data of PBBA consumption were provided by Shandong Yuwang Ecological Food Industry Co., LTD, while the data of beef consumption in China during the past two years were based on the FAO data from 2022 to 2023 (Figure 1).

The data of beef consumption from 2024 to 2030 are based on projections from the Food and Agriculture Organization of the United Nations according to the formula (1).

$$S_{2022} = PR_{2022} + IM_{2022} - EX_{2022} \quad (1)$$

where S_{2022} was the apparent beef consumption in 2022 (t), PR_{2022} was the beef production in 2022 (t), IM_{2022} was the beef import volume in 2022 (t), while EX_{2022} was the beef export volume in 2022 (t).

The alleviating ability of substitution of beef with PBBA at different ratios on the negative environmental impacts was calculated by the formula (2)

$$X_n = (S_{2022} * a\%) * X_1 + S_{2022} * (1 - a\%) * X_2 \quad (2)$$

where S_{2022} represented the apparent beef consumption in 2022 (10 kt) (The consumption data for 2022 was set to be

consistent with the time frame of the 2022-2023 consumer survey), $a\%$ represented the beef substitution ratio with PBBA, while X_1 and X_2 represented the corresponding environmental index equivalent of PBBA and beef calculated by this model, respectively.

2.4. Data Analysis

The software Simapro 9.0 was utilized to calculate the environmental impact factors during the production process of beef and PBBA. As shown in Table 1, 12 environmental impact indicators were selected according to the research of [25]. The databases of Simapro software analysis contained Agri-footprint economic unit, Ecoinvent 3 cut-off by allocation-unit, EU&DK input Output Database and USLCI, while the analysis method was carried out according to ReCiPe 2016 midpoint (H) method [26]. For the sensitivity analysis of the system, the software Python 3.11.4 was used to calculate 50,000 Monte Carlo analyses [27]. The results of Simapro analysis and sensitivity analysis were processed using OriginPro 9.8.5 software. Table 4 showed the parameters for sensitivity analysis.

Table 4. Parameters of sensitivity analysis in experimental model

Object	Parameters	Baseline value
Plant-based beef analogues	Electricity	1.715 kWh
	Soybean	0.56 kg
	Fertilizer as N	0.025 kg
	Fertilizer as P ₂ O ₅	0.0625 kg
	Fertilizer as K ₂ O	0.025 kg

2.5. Research on Chinese Consumer Behavior

In 2022-2023, based on consumer behavior study [28] and the LCA indicator framework [25], a survey was conducted on the consumption behavior of PBBA among

consumers in 18 cities in western, central and eastern China based on four dimensions (price, nutrition and health, flavor authenticity, and overall satisfaction) in the form of a questionnaire among people aged 15-30, 31-50, and 51-65. SPSS 19.0 were used for regression analysis of the survey data to determine the significant impact of each variable on the dependent variable.

3. Results and Discussion

3.1. Effects of the Production of Beef and PBBA on the Atmospheric Ecology in Different Countries

Global warming (GW) 100, ozone formation (OF) and fine particulate matter formation (FPMF) are the typical indicators of atmospheric ecology. Global warming potential (GWP) represents the amount of energy absorbed (radiative efficiency) over a given time horizon relative to that of CO₂, the most common metric uses a time horizon of 100 years (GWP 100) [29]. Ozone is a major air pollutant in urban environments, with increasing trends reported globally over recent decades. Volatile Organic Compounds (VOCs) are an important factor in

promoting the photochemical formation of tropospheric ozone [30]. Industrial emissions, vehicle exhausts and biomass burning are the main factors contributing to the formation of fine particulate matter [31].

The effects of beef and PBBA production on the GW100, OF and FPMF in 12 countries were presented in Figure 2. In terms of the whole production process of 1 kg of beef and PBBA, the average GW, OF or FPMF value of beef were 16.5-, 4.4- or 22.9- fold higher than that of PBBA, respectively. The GW 100 values of PBBA in different countries varied from 0.8 kg CO₂eq (NZ) to 3.3 kg CO₂eq (AR), which was in line with the results of previous studies (0.2-2.64 kg CO₂eq) and confirmed the accuracy of our model (Table 5). OF values were in the range of 0.002 kg NO_xeq (NZ) and 0.02 kg NO_xeq (US), whilst FPMF values ranged from 0.001 kg PM_{2.5}eq (AR) to 0.006 kg PM_{2.5}eq (ZA). In terms of beef production, the GW 100 values of different countries were in the range of 27.5 kgCO₂eq (DE) - 35.7 kgCO₂eq (NG) and in accordance with the data of previous research (13-48.4 kgCO₂eq) (Table 5). The GW100 value in NG was the highest among all countries, while the OF (0.07 kg NO_xeq) or FPMF value (0.19 kg PM_{2.5}eq) in CN was higher than that of other countries.

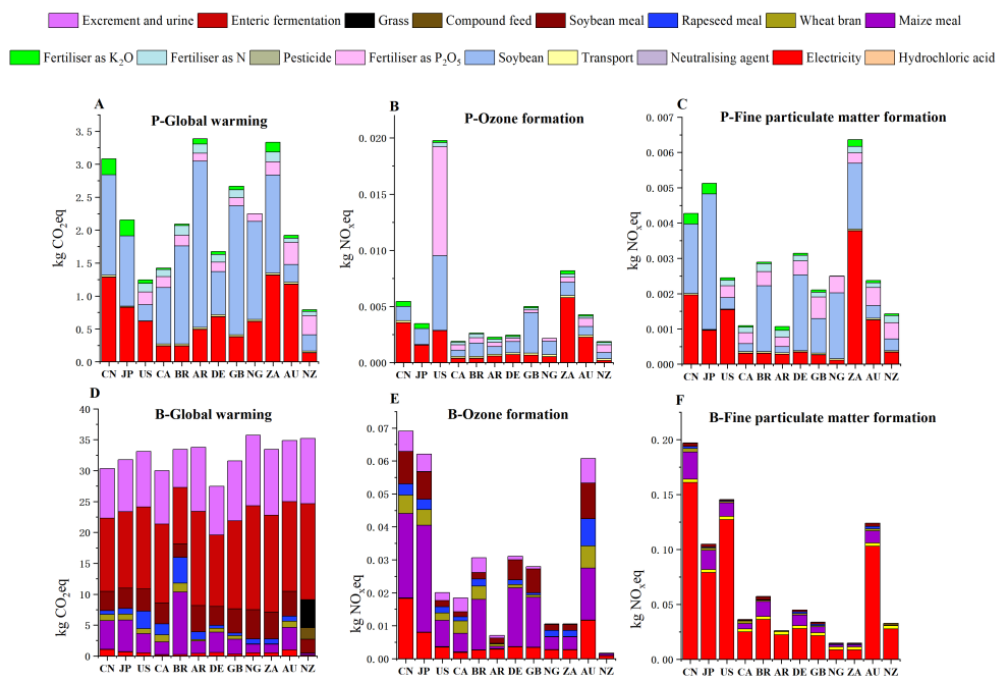


Figure 2. Effects of the production of beef and plant-based beef analogues on the atmospheric ecology in different countries. Note: P represented for plant-based beef analogues, B represented for beef

Table 5. Comparison of the data of carbon emissions from beef and PBMA in previous studies with our study

Country	Carbon emission (kg CO ₂ eq/kg)	Main raw materials	Pocessing methods	References
PBMAs				
Britain	MA: 2.33	TVP, SPI, WG and CS	HME	[32]
Switzerland	SBP: 0.4 - 0.53	TVP, SPI	HME, TVP	[33]
Italy	SBF: 0.46 - 0.5 /	Soy	-	[34]
Britain	SBF: 0.26 - 0.37	Soy and lentils	-	[35]
German	PBS: 0.2 - 2.1	Grains (beans) and flours	-	[36]
America	MA: 1.44 - 2.64	Soy, wheat	-	[37]
Sweden	PBMAs: 1.7	-	-	[38]

Country	Carbon emission (kg CO ₂ eq/kg)	Main raw materials	Pocessing methods	References
12 countries	PBBA: 0.8 - 3.4	Soy Beef		
America	BP: 35.6			[39]
Italy	LW: 17.62- 26.30			[40]
Italy	LW: 18.21 (CS), 24.62 (OS)			[41]
Japan	CCSW: 28.9 (CS), 29.3 (OS), 35.1 (NS)			[42]
America	Carcass: 48.4			[43]
	CW: 13-39			[44]
Norway	22.73 (DUP) - 33.75 / (SBP)			[45]
Brazil	LW: 18.3 - 42.6			[46]
Japan	28.9 - 35.1			[42]
12 contries	27.5 - 35.7			

Note: PBMA: plant-based meat analogues, TVP: texturised vegetable protein, SPI: soy protein isolate, WG: wheat gluten, CS: cornstarch, HME: high moisture extrusion, MA: meat analogue, BBP: beef burger patties, SBF: soy-based food, SBP: soy burger patties, LW: live weight, OS: organic system, NS: non-organic system, CS: conventional system, cold carcass steer weight / carcass weight (CW), DUP: dual-purpose production, SBP: specialized beef production, PBS: plant-based substitutes

During the processing of PBBA, raw soybeans and electricity played the most important roles in three atmospheric indicators, followed by fertilizer (including K₂O, N and P₂O₅). Figure 2A showed that the soybean production contributed to more than 70% of GW 100 in AR during the manufacturing process of PBBA. AR is the third-largest global exporter of soybeans, in which farmers prefer to grow soybeans and convert pasture land to farmland for soybean production due to food policy uncertainty [47]. As shown in Figure 2B, the indicator values of soybean production and electricity accounted for 14.5% and 70.7% in the OF value of ZA, respectively. However, the fertilizer in the form of P₂O₅ significantly influenced the OF value in GB during PBBA production, likely because phosphate facilitates oxidative hydration reactions and promotes ozone formation [48]. The FPMF value of ZA (0.006 kg PM_{2.5}eq) is much higher than that of other countries (Figure 2C), as 69% of its electricity is generated from coal. [49].

During beef production, the indicator values of the enteric fermentation [27.3% (BR) to 47.0% (NG)] as well as the total feed were mainly contributed to the GW 100 values [19.5% (NG) to 53.5% (BR)] in most countries (Figure 2D). The extensive pasture-based system in BR utilized a series of forage plants adapted to climate and soil conditions, which limited its access to purchased inputs [50]. The indicator of maize meal played a more important role in the greenhouse gas emissions in BR rather than the electricity indicator as well as the excrement and urine during beef production. Semi-intensive farming practices allowed intestinal fermentation in meat industries of BR to produce minimal carbon emissions [51]. It could be noticed that the GW 100 value for beef production in NG and NZ were significantly higher than those in other countries. The high value of greenhouse gas emissions of NG are attributed to intestinal fermentation (47%) and inefficient feed [22]; in NZ, it is due to differences in pasture management systems [52]. As shown in Figure 2E, the indicator values of soybean and maize meal in beef production mainly contributed to the increase of OF value [41.6% (NZ) - 84.9% (GB)] in 12 countries, while the percentage of

electricity value [41.6% (NZ) - 84.9% (GB)] was mainly contributed to the increase of FPMF values in these countries.

3.2. Effects of the Production of Beef and PBBA on the Terrestrial Ecology in Different Countries

The indicators for terrestrial ecology mainly included terrestrial ecosystems (TE), terrestrial acidification (TA), terrestrial ecotoxicity (TT), and land use (LU). Agricultural production requires large amounts of land resources and is linked to significant levels land use change, as well as deforestation and peatland drainage [53]. The direct or indirect emissions from planting and breeding activities have led to challenges such as antibiotic resistance and zoonotic diseases, thereby damaging TE, including biodiversity, water quantity and quality, pollination, pests, etc. [54]. TA was seen as a result of low sulfur-containing petroleum products and petroleum combustion in production and transportation equipment [55]. TT is mainly caused by the use of fertilizers in agricultural production or arising from heavy metal emissions [56].

It has been shown in Figure 3A that the TE value in ZA was the highest during the production of PBBA, while NZ showed the lowest TE value. Due to the lack of planting technology and the shortage of local soybean supply [57], the soybean products in ZA displayed a competitive disadvantage, which may be linked to the high TE value. In terms of beef production, the TE value in NZ was the lowest among all countries. However, JP showed the highest TE value during the production of beef (Figure 3E). The livestock production in JP significantly influenced reactive nitrogen flows (the migration and transformation processes of all reactive nitrogen except nitrogen gas (N₂) in agricultural and food systems, including crop cultivation, livestock production, food processing and consumption, etc.) in these countries due to 85% of its concentrated feeds was imported [58]. It was worthwhile to note that the TE value in NZ during the production of PBBA was 1.71-fold higher than that of beef. Moreover, the indicator values of soybean and

electricity contributed the most to the TE values of PBBA because the production of PBBA was supported by the traditional crop cultivation as well as processing equipment that consumes electricity [59].

The value of TA was closely associated with the emission of SO₂ produced by human activity. Figure 3B showed that the TA value in ZA during the production of PBBA was 5.38-fold that of AR, the high TA value of ZA and its heavy reliance on coal power (86%) are associated with SO₂ emissions [60]. Similarly, the highest contribution of all input and output factors to TA was electricity indicator, followed by soybean indicator. Regarding beef production, the TA value in CA was the highest among all countries, while the electricity generation and maize meal production mainly contributed to the emission of SO₂. Thermal power generation was the main source of electricity in most countries (except for CA, where hydropower is the main source of electricity), as the raw materials for thermal power generation mainly contained coal, oil and natural gas [61]. Based on BP Statistical Review of World Energy [61] on the proportion of coal power in various countries, ZA (86.0%), CN (64.7%), AU (56.3%) and DE (28.0%) utilized coal as the main material for thermal power generation. With increasing coal consumption around the world, SO₂ pollution has aggravated [60]. Thereby, it could be noticed that CN and ZA had the highest SO₂ emission during the production of PBBA and beef, respectively.

Terrestrial ecotoxicity (TT) is primarily driven by agrochemical inputs in feed and crop systems. The mean TT value for PBBA production across 12 countries was 6.2 kg 1,4-DCB—significantly lower than beef production's 19.3 kg 1,4-DCB (Figure 3C). JA's elevated TT burden (2.29× higher than NG) stems from intensive

soybean cultivation requiring high pesticide/fertilizer inputs (58.98% contribution from soybean production), compounded by electricity-intensive processing (34.16% contribution). NZ's minimal TT impact in beef production (only 6.31% of CN's value) reflects its pasture-based systems with limited concentrate feed use, whereas CN's industrialized feed sector contributes 25.83% of TT via soybean meal and 19.02% via rapeseed meal (Figure 3G). This aligns with a study [62] which confirming that developed feed industries—characterized by synthetic fertilizer dependency—amplify ecotoxicity risks. Notably, TT variations correlate with national agricultural intensity, countries with higher compound feed utilization (e.g., CN, JP) exhibit disproportionately elevated TT levels versus pasture-reliant systems (e.g., NZ).

Soybean production played major role in the LU level during the production of PBBA. It was shown that the LU level both in JP and AR during the production of PBBA were 1.1-fold higher as compared with that in NZ. Since 1961, the soybean production in JP has grown slowly, the stagnation might be caused by the soil fertility and water resources constraints [63], which reduced the LU efficiency. The LU level in NZ during beef production was 91.3% lower compared to that of BR. As one of the largest beef exporters in the international market, the beef production in BR required extensive ranching area [64]. However, the decrease of the number of beef cattle and weaned calf lead to a LU reduction for beef cattle farming [65]. Based on the data of terrestrial ecology, the indicators for electricity and soybean production were main factors to the increase of TE, TA, TT and LU levels during the production of PBBA, whilst the indicators for electricity, maize and soybean meals greatly contributed to the increase of these indicators in beef production process.

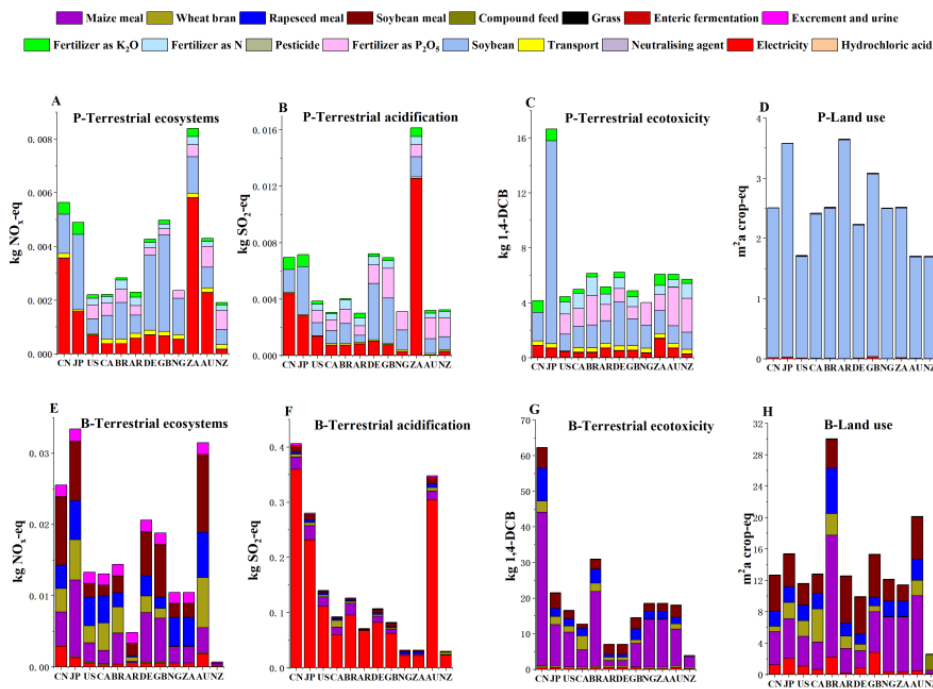


Figure 3. Effects of the production of beef and plant-based beef analogues on the terrestrial ecology in different countries

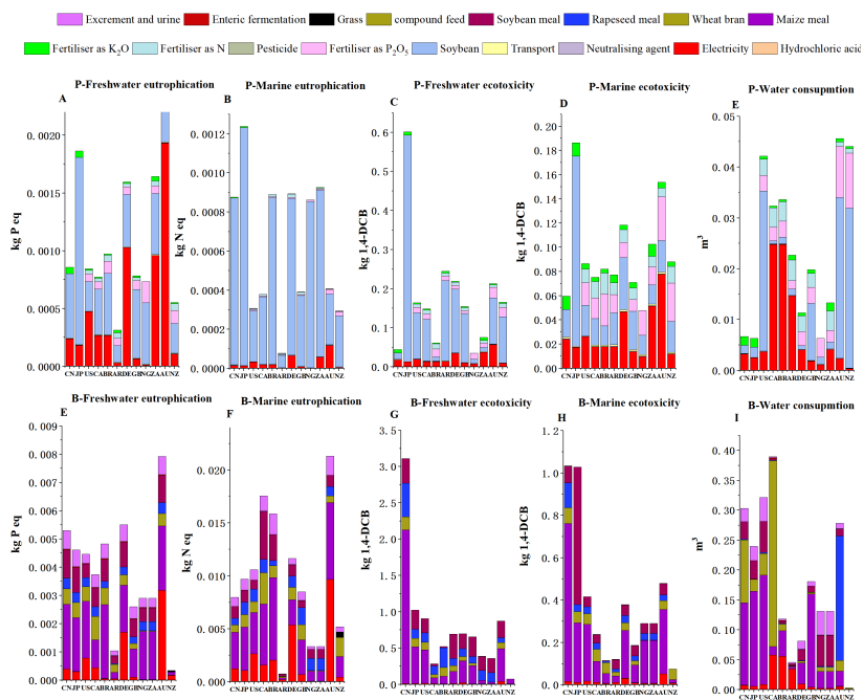


Figure 4. Effects of the production of beef and plant-based beef analogues on the water ecology in different countries

3.3. Effects of the Production of Beef and PBBA on the Water Ecology in Different Countries

Effects of the production of beef and PBBA on five water ecology indicators were evaluated in our research as well, including freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FT), marine ecotoxicity (MT) and water consumption (WC). The water eutrophication caused by excessive nitrogen and phosphorus levels resulting from human activities is an important factor affecting the water quality [66]. When drugs and chemicals are released into the aquatic environment, either in their original form or as metabolites, the resulting ecological toxicity is known as freshwater or marine ecotoxicity [67]. The impact of water consumption is estimated as the amount of water evaporated, incorporated into products, transferred to other watersheds or disposed into the sea and no longer available [68].

The average values of FE, ME, FT, MT, and WC during beef production were 2.6-, 18.8-, 8.9-, 3.4-, and 7.8-fold higher than those of PBBA (Figure 4), respectively. Consistent with data from atmospheric and terrestrial ecology, the indicator values for soybean and electricity played significant roles in the impact of PBBA production on water ecology in 12 countries, whereas indicators for maize and soybean meals were crucial for the enhancement of five water ecology indicators during beef production.

Excessive nutrients in wastewater, a result of human activities, significantly promote the growth of microorganisms and algae. This overproduction can cause a series of detrimental effects on the ecosystem [69]. In the context of FE and ME within the PBBA production sector, the FE value in AU was 7.56 times higher than that in AR. Meanwhile, JP had the highest ME value at 0.001 kgNeq among the 12 countries studied (Figure 4A and

Figure 4B). Similarly, the FE and ME values in AU during PBBA production (FE - 0.002 kg Peq, ME - 0.0004 kg Neq) were notably higher than those of other countries. In AU, the indicator for electricity accounted for 81.58% of the FE values during PBBA production. Additionally, the indicator for soybean production accounted for 1.05% of the ME values in JP during beef production, whereas electricity and maize meal constituted 45.36% and 34.02% of the ME values in AU during beef production, respectively (refer to Figure 4E and Figure 4F). The historical use of phosphorus fertilizers has bolstered grazing agriculture in certain regions of AU. However, elevated soil phosphorus levels have led to an increased risk of eutrophication [70].

The values of FT and MT refer to the potential impact of toxic chemical emissions on freshwater and marine ecosystems [71,72]. The FT and MT values in JP during the production of PBBA were the highest among all countries, while CN exhibited significantly higher FT and MT values than other countries during beef production (Figure 4C and Figure 4D). The average proportions of soybean production in FT and MT values of JP during the production of PBBA were 58.98% and 34.16%, respectively. Meanwhile, the proportion of soybean meal and rapeseed meal accounted for 25.83% and 19.02% of FT and MT values in CN during beef production, respectively (Figure 4G and Figure 4H). Water conservation is essential for the achievement of global Sustainable Development Goals (SDGs). During the production of PBBA, the WC value of these countries ranged from 0.006 m³ (NG) to 0.046 m³ (AU), while the indicators for soybean production and electricity mainly contributed to the increase of WC value in countries. In terms of beef production, it is the least water-efficient among the production of livestock products, and the WC is primarily to satisfy its irrigation requirements during feed production [73]. The range of WC value during beef

production was between 0.003 m³ (NZ) and 0.39 m³ (CA). Figure 4I showed that maize meal (accounting for 17.2% - 94.6%) played a major role in the increase of WC values of different countries. Whereas, compound feed greatly contributed to the WC values in some countries as well. It was worth mentioning that the proportion of compound feed accounted for 84.2% in the composition of WC in CA during beef production. In recent years, urbanization, mining, transportation, as well as oil and gas development, have occupied the land used for feed production in CA, the reduction in both supply and quality of feed required a compound feed to satisfy the need of beef production [74].

3.4. The Difference Ratio of effects of the Production of Beef and PBBA on the Environmental Indicators in Different Countries

The difference ratio of effects of the production of beef and PBBA on the environmental indicators in different countries were further compared (Figure 5). It could be observed that the difference in effects of the production of beef and PBBA on the LU, OF, FE, TE and GW 100 values in 12 countries were similar, while there were significant difference in other indicators. It could be explained by the differences in the production structure and production capacity in these countries [75]. Notably, the difference ratio of effects of the production of beef and PBBA on a series of environmental indicators in AU (TA, 1.0% - 107.5%) and CN (MT, -0.1% - 16.4%, FT, -0.5% - 69.5%, TT, 0.3% - 14.0%) were much larger than other countries. Therefore, it was inferred that consumption substitution of beef with PBBA in different countries might effectively help achieve global SDGs.

The difference ratios of the effects of beef and PBBA production on environmental indicators across various countries were further compared (Figure 5). It was observed that the effects of beef and PBBA production on LU, OF, FE, TE, and GW 100 values in 12 countries were similar, whereas significant differences were noted in other indicators. These differences could be attributed to the varying production structures and capacities among these countries [75]. Notably, the difference ratios of the effects of beef and PBBA production on environmental indicators in AU (TA, 1.0% - 107.5%) and CN (MT, -0.1% - 16.4%; FT, -0.5% - 69.5%; TT, 0.3% - 14.0%) were much larger than in other countries. Consequently, it was inferred that substituting beef consumption with PBBA in different countries could effectively aid in achieving global Sustainable Development Goals (SDGs).

3.5. A Case Study: Sustainability Benefits of Consumption Substitution of Beef with PBBA in China

Based on the LCA results from 12 countries, this section takes China as an example to quantify the environmental benefits of PBBA replacing beef at various consumption levels (0%, 25%, 33.3%, 50%, 100% of PBBA consumption) from 2022 to 2030 (Figure 6). Link the emission reduction data (128 million tons of CO₂) to China's "carbon neutrality goal", and explore the

contribution degree of alternative solutions to achieving SDG12/SDG13.

It was demonstrated that the adverse effects of beef consumption on atmospheric, terrestrial, and water ecosystems gradually decreased with an increasing consumption substitution ratio of PBBA. The complete substitution of beef with 100% PBBA consumption in 2022 resulted in a reduction of 12.796 million tons of CO₂ (Figure 6A), equivalent to 2.04% of China's agricultural emissions in 2019 [76]. It appeared that substituting 1% of beef consumption with PBBA each year could lead to a reduction of 0.4-0.7% in China's agricultural carbon emissions. In terms of all environmental indicators, the FT value decreased most significantly after substituting beef with PBBA, while the TE value was least affected. According to a study [62], the FT value primarily originated from the use of industrial energy in feed production for cattle. When beef consumption was replaced by PBBA, the FT value would significantly decrease due to the reduced feed demand. When beef consumption was substituted by 100% PBBA in China in 2030, the GW, OF, TE, TA, FE, ME, TT, FT, MT, LU, FPMF, and WC values were 5.4%, 5.5%, 4.6%, 5.9%, 5.0%, 5.3%, 5.6%, 5.9%, 5.6%, 4.8%, 5.9%, and 5.9% lower than those of the control, respectively. It showed that the consumption substitution of beef with PBBA in China would have more beneficial effects on atmospheric ecology than on water and terrestrial ecology. Most nitrogen in animal feed was lost [77] in the form of nitrogen compounds (NH₃ and N₂O) through volatilization (41%), followed by nitrate (NO₃⁻) through leaching into the soil (40%) and waste or wastewater during processing (15%). Therefore, the carbon and nitrogen emissions of beef production in China could be significantly reduced by substituting consumption with PBBA.

3.6. Sensitivity Analysis of Evaluation System

Figure 7 indicates that the variation in different environmental indicators remained relatively stable with a 20% increase in the input parameter value, suggesting that these input parameters had a minimal impact on the output data during the production of PBBA in CN [78]. Notably, only minor changes in ME, OF, TA, FE, LU, and ME values were observed after increasing the value of electricity, soybean raw materials, nitrogen fertilizer, phosphate fertilizer, or potassium fertilizer during the production of PBBA. In contrast, the GW100, TT, TE, FT, FPMF, and WC values varied to a greater extent than other values, likely due to their closer correlation with the input parameters.

In terms of the effects of increase of soybean proportion during the production of PBBA on the environmental and human health indicators in CN, the variation range of different indicators was between -10.0% (OF) and -80.7% (FE) (Figure 7). Among these indicators, TT, TE, FT, MT, FPMF and WC values varied to a greater extent. During soybean production, the utilization of chemical fertilizers and pesticides mainly caused the water and terrestrial ecological impacts as well as human health. For instance, ME increased by only 4.4% at a 20% increase of soybean proportion, while FE value increased by 80.7%. The difference might be associated with the freshwater

resource requirement rather than ocean resource during the planting of soybeans. Regarding the effects of increase of electricity during the production of PBBA on the output results in CN, the variation range of data changed from -3.8% (GW) to 67.0% (TA) (Figure 7). It was worthwhile to note that the change of GW 100, TT, TA, TE, LU, FT and FPMF values were larger than other values when the input parameter increased by 20%. As the main raw material for the generation of thermal power in CN, the consumption of coal could significantly lead to CO₂ and SO₂ emissions [79]. Therefore, the change of input value of electricity induced a significant variation of atmospheric and terrestrial indicators. It could be inferred that TA might be greatly weakened by consumption substitution of coal with natural gas as the main thermal

power generation in CN. Alternatively, the effects of change in input level of three fertilizers during the production of PBBA in CN on the environmental and human health indicators were similar. Specifically, the variation range of different indicators after increasing by 20% of fertilizer as K₂O, N or P₂O₅ was between 3.03×10^{-6} and 5.14×10^{-6} , 3.36×10^{-6} and 5.13×10^{-6} or 3.69×10^{-6} and 6.96×10^{-6} , respectively. It was observed that the change of TT, TE, FT and WC values were larger than other values, which was in consistent with our previous results. After decades of utilization, the addition of trace elements in fertilizers might lead to a deterioration of soil quality. The accumulation of these elements in the food chain had the potential to cause chronic diseases of the kidney, lung, cardiovascular and musculoskeletal systems [80].

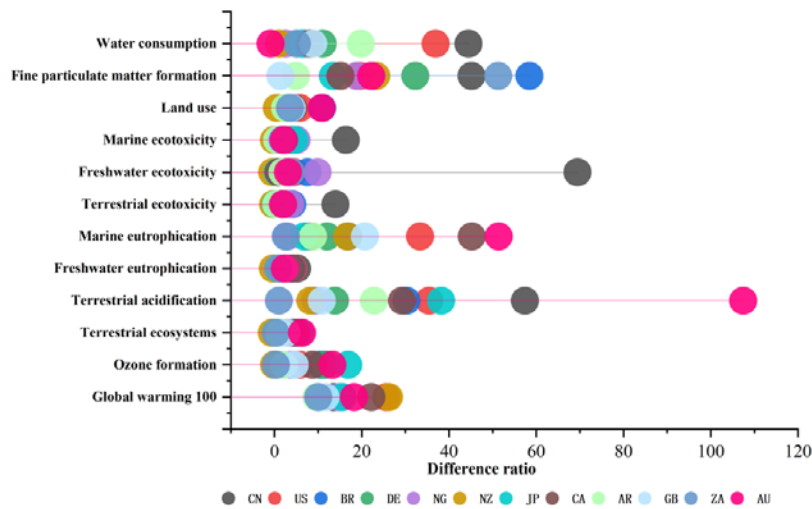


Figure 5. The difference ratio of effects of the production of beef and PBBA on the environment indicators in different countries

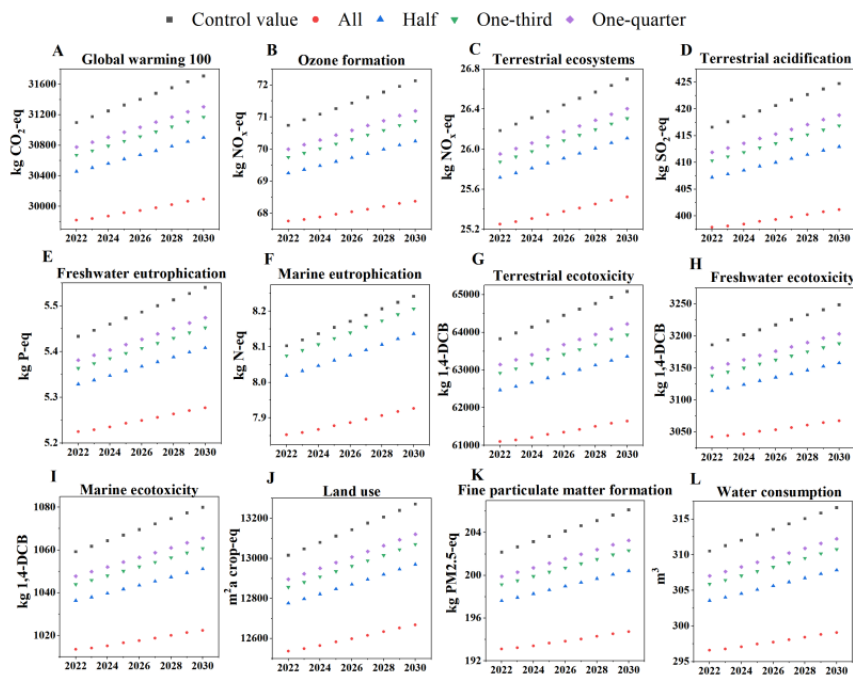


Figure 6. The consumption substitution effects of beef with PBBA on alleviating negative environment impacts in CN from 2022 to 2030

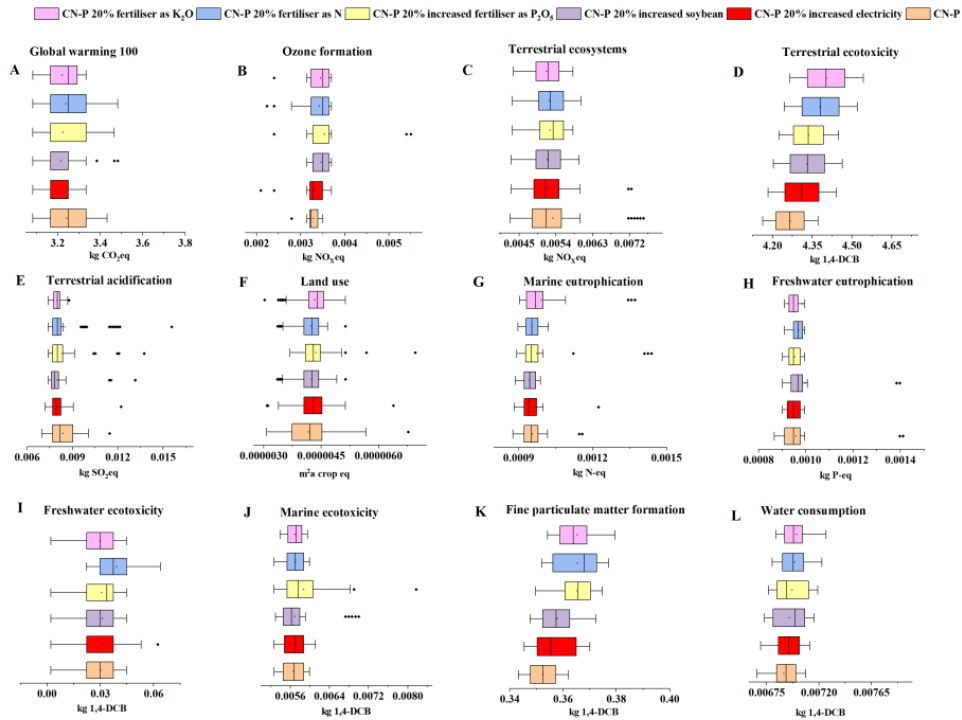


Figure 7. Sensitivity analysis of the experiment model

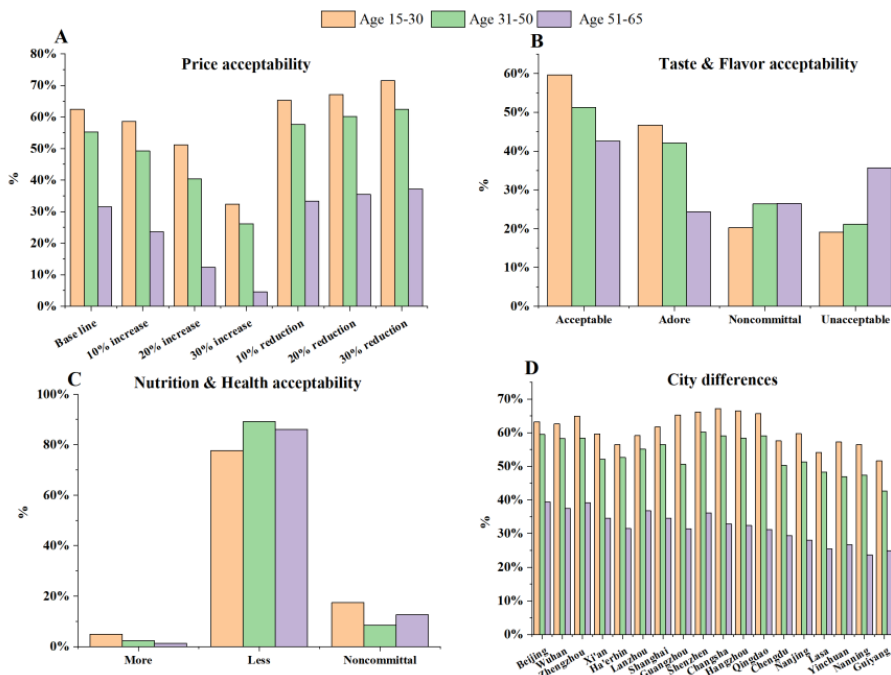


Figure 8. The choice and preference factors of consumers in 18 cities of China

3.7. Analysis of Chinese Consumer Behavior

Based on SPSS regression analysis of consumer behavior data, the acceptability of PBBA consumption is significantly affected by price, taste & flavor (TF), nutrition & health (NH) and city differences (Figure 8). There are obvious differences in price elasticity among different age groups (Figure 8A), among which the 15-30 age group is the most sensitive to price changes: when the price of PBBA increased by 10%, the acceptability of this

group decreased by about 12.3% ($\beta = -0.68, p < 0.01$), while that of the 51-65 age group decreased by only 5.4% ($\beta = -0.31, p < 0.05$), which may be related to the lower disposable income and more rational consumption habits of the younger group [28]. TF preference is the core barrier across age groups (Figure 8B), the data show that the proportion of consumers with "unacceptable taste" of PBBA accounts for 38.7% ($p < 0.001$), especially in second-tier cities that prefer traditional cooking methods (such as Chengdu and Xi'an), the negative impact of TF factors ($\beta = -0.53$) is significantly higher than that of first-

tier cities ($\beta = -0.29$). Although the direct effect of NH labels on overall acceptance was weak ($\beta = 0.11$, $p = 0.07$) (Figure 8C), its effect was significantly enhanced in cities with high education levels ($\beta = 0.24$, $p < 0.05$), suggesting that health marketing needs to be designed for specific populations.

City differences further reveal the complexity of market stratification (Figure 8D). The response of northern cities (such as Harbin and Lanzhou) to price concessions is 17% higher than that of southern cities (Guangzhou and Shenzhen), which may be related to economic structure and food culture; However, consumers in inland cities (such as Zhengzhou and Changsha) are more likely to be driven by taste improvement ($\beta = 0.42$ vs. Coastal city $\beta = 0.21$). It is worth noting that in the subsidy policy simulation, a 10% price reduction can increase the acceptance of third-tier cities (such as Nanning and Guiyang) to 0.67 (baseline 0.51), but only 0.59 (baseline 0.55) in first-tier cities, suggesting that the price leverage effect of sinking markets is more significant. In summary, the promotion of plant meat needs to adopt a differentiated strategy: the implementation of stepped subsidies for young and low-income groups, the priority of optimizing product taste in second-tier and inland cities, and the strengthening of health and environmental protection narratives in first-tier cities, in order to break the triple bottleneck of "price - taste - cognition".

3.8. Policy Implications

The findings of this study underscore the urgent need for a multi-tiered policy framework to accelerate the transition from beef to PBBA in China, addressing environmental, economic, and social dimensions simultaneously. Building on the regional heterogeneity of production impacts, consumer behavior dynamics, and sensitivity analysis outcomes, we propose an integrated policy strategy that aligns with China's Dual Carbon Goals (2030/2060) and Sustainable Development Agenda.

First, addressing the coal-electricity lock-in in PBBA production is critical to maximizing emission reductions. Our analysis reveals that coal-dominated power grids in northern China amplify PBBA's carbon footprint by 64.7%, undermining its environmental advantages. To mitigate this, policymakers should prioritize regional energy transition subsidies targeting PBBA manufacturers in coal-dependent provinces (e.g., Shanxi and Inner Mongolia). For instance, tax rebates or low-interest loans could incentivize factories to adopt renewable energy microgrids powered by solar or biogas, particularly in regions with high solar irradiance [81]. Concurrently, integrating PBBA production into China's national carbon trading system would internalize the environmental costs of coal-based electricity [82], creating financial disincentives for carbon-intensive energy use.

Second, soybean import reliance—85% sourced from deforestation-prone regions like Brazil and Argentina—poses a systemic risk to PBBA's sustainability. To decouple soybean supply chains from ecological degradation, China should establish bilateral sustainability partnerships with key exporters. This could involve: negotiating "zero-deforestation" trade agreements that mandate satellite-monitored compliance for soybean

plantations [83]. Funding agroecological training programs for Brazilian farmers to adopt silvopastoral systems, which integrate soybean cultivation with native vegetation [84]. Launching a program such as "Soybean Certification", where PBBA products using certified sustainable soy receive preferential tariff rates [85] or consumer-facing eco-labels [86]. Such measures would align with global initiatives like the EU Deforestation Regulation (EUDR), positioning China as a responsible player in transnational supply chain governance.

Third, consumer acceptance barriers—particularly price sensitivity and taste skepticism—require targeted behavioral interventions. Our survey data indicate that a 10% price reduction boosts PBBA adoption in low-income regions by 17%, yet blanket subsidies risk exacerbating fiscal burdens [87]. Instead, a graded subsidy system should be implemented: tier 1 cities (e.g., Beijing, Shanghai) focus on "nudging" high-income consumers through carbon footprint labeling and PBBA integration into premium dining platforms (e.g., Meituan's "Green Eats" section). Tier 3-4 cities and rural areas: deploy direct vouchers or conditional cash transfers tied to PBBA purchases, prioritizing regions with high beef consumption (e.g., Xinjiang, where per capita beef intake is 2.3× the national average). Youth-centric campaigns: leverage social media influencers and gamified apps to rebrand PBBA as a "tech-savvy" choice, capitalizing on younger demographics' openness to innovation (45% acceptance rate among ages 18–30).

Fourth, safeguarding livelihoods in traditional livestock-dependent communities is essential for a just transition. The projected displacement of 2.1 million smallholder cattle farmers in western China necessitates retraining and diversification programs: establish regional "Agri-Tech Hubs" to train farmers in PBBA ingredient cultivation (e.g., soy, pea) or alternative livelihoods like eco-tourism [88]. Introduce transitional income support funded by a "PBBA Innovation Tax" levied on large meat processors [89], ensuring equity between industrial and rural stakeholders. Pilot contract farming models where farmers supply non-GMO soy to PBBA manufacturers under fixed-price agreements [90], reducing market volatility risks.

Fifth, public procurement policies can catalyze market scaling while ensuring nutritional equity. Integrating PBBA into the National School Lunch Program would simultaneously reduce childhood obesity rates (linked to excessive red meat consumption) and normalize plant-based diets [91]. Initial pilots could target provinces with high childhood obesity rates (e.g., Shandong, 19.2%), pairing PBBA meals with educational modules on sustainable eating [92]. Similarly, mandating PBBA in government cafeterias would create stable demand [93], encouraging private sector investment in R&D for texture and flavor optimization—addressing the 38.7% consumer rejection rate due to "unacceptable taste."

Finally, strengthening cross-ministerial coordination is vital to avoid policy fragmentation. A National PBBA Task Force—comprising representatives from the Ministry of Ecology and Environment, Ministry of Agriculture, and National Development and Reform Commission—should oversee the alignment of fiscal incentives, agricultural subsidies, and climate targets. This body could also

facilitate international knowledge exchange, such as adopting Canada's success in leveraging pea protein for PBBA [94].

By interweaving these strategies, China can transform PBBA from a niche product into a cornerstone of its low-carbon food system, achieving synergies between emission reduction, rural revitalization, and global leadership in sustainable agri-food innovation. This approach not only addresses the immediate challenges identified in our study but also lays the groundwork for a resilient, equitable protein transition in the face of climate uncertainty.

4. Conclusions

This study reveals the core contradiction in the promotion of plant-based beef analogues (PBBA) in China: although Life Cycle Assessments (LCA) from multiple countries have confirmed their environmental benefits (a 1% annual substitution rate can reduce agricultural emissions by 0.4-0.7%, and cumulative emission reduction of 12.8 million tons of CO₂ by 2030), their actual adoption is constrained by deep-seated social and cultural dynamics. Taste authenticity becomes a key barrier. In traditional food hubs like Chengdu, 41.5% of consumers reject PBBA because of its texture not matching traditional meat; cultural identity further mediates 62% of flavor doubts, rendering environmental publicity ineffective. At the same time, economic vulnerability exacerbates inequality: the price sensitivity of low-income young people is three times that of the elderly group, and they face the risk of exclusion from sustainable diets. Regional differences further complicate the market - northern consumers prioritize price, while southern consumers prioritize sensory familiarity, and the health narrative only touches upon the urban elite group.

To address these challenges, the study proposes a culturally embedded solution: through chef collaboration to develop localized recipes, campus programs to utilize peer influence to cultivate young acceptance, and combined with tiered subsidies (targeted coupons for low-income groups, carbon labels incentives for first-tier cities). Policies need to simultaneously solve the supply chain paradox: the reliance on coal and electricity in northern China increases the carbon footprint of PBBA by 64.7%, requiring renewable energy subsidies; while the deforestation risk of soybean imports requires the establishment of a "zero deforestation certification" trade framework. Ultimately, coordinating ecological goals with dietary traditions requires placing cultural identity at the core of sustainable governance, which provides a key paradigm for global dietary transformation.

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