Dean&Francis
ISSN 2959-409X

Environmental Impact of the Plant-Based Meat Alternatives

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Abstract:
With global population growth and rising consumption levels, the demand for meat has increased dramatically. Traditional animal husbandry, due to its high resource consumption and significant environmental pressures—such as substantial greenhouse gas emissions, land occupation, and water resource waste, has become difficult to sustainably meet future demands. As an emerging alternative protein source, plant-based meat substitutes can significantly reduce resource consumption and alleviate environmental pollution by extracting protein from plants and simulating the taste of meat. Based on the life cycle assessment method, this paper systematically compares the environmental impacts of plant-based meat substitutes and traditional pork on greenhouse gas emissions, energy use, water consumption, and land use during the production process. The results indicate that plant-based meat substitutes exhibit superior environmental performance in all dimensions. Furthermore, this article explores the current challenges in the industry, such as insufficient consumer acceptance, and proposes corresponding promotion strategies, providing both a theoretical foundation and practical references for the development of plant-based meat substitutes.

Keywords: List the; keywords covered; in your paper.

1. Introduction

The United Nations announced on November 15, 2022 that the world's population had reached 8 billion, marking a new stage in human development, which is attributed to the rapid advancements in health, nutrition, and technology. According to the UN's „World Population Prospects 2024: Highlights", the peak of world population growth is predicted to occur in 2084, when the global population is expected to reach 10.3 billion [1]. This means that people will face extremely frightening consumption of food resources, especially in the demand for protein products. Recently, an important source of protein intake has been animal products, with the mainstream source being traditional livestock farming. However, traditional livestock farming is a significant source of greenhouse gas emissions, accounting for 14.5% of global greenhouse gas emissions, which is close to the 16.2% emitted by transportation [2]. At the same time, animal husbandry

ISSN 2959-409X

has also caused an extremely huge burden and brought problems that cannot be ignored. For example, animal husbandry occupies 77% of agricultural land, occupies 67 million square kilometers of land (accounting for 45% of the earth's land area), consumes 30% of water resources, and produces a large amount of greenhouse gases. Animal products only provide 17% of food and 40%-58% of protein for all mankind, which shows that the efficiency of animal husbandry is extremely low. To address the rapid increase in protein consumption driven by the future sharp population growth, the negative environmental impact of traditional animal husbandry is bound to continue to expand. Specifically, the land area occupied by traditional animal husbandry will be even larger, the water resources consumed will be more, and the greenhouse gases emitted will be greater. Recently, in order to address the growing global demand for protein sources, create a more efficient way of producing meat products, and reduce the environmental impact of producing protein meat products, people have turned their attention to the plant-based meat industry, of which plant-based meat is an important component. Plant-based meat is exceptionally nutritious, healthy, and safe to eat, and is more readily accepted by consumers than insect protein-based meat. Consequently, a wave of research into plant-based meat has swept across China and abroad, focusing on production technology development, product development, and environmental impact. Life Cycle Assessment (LCA) is a technology and method used to assess the impact of a product during its entire life cycle, from the acquisition of raw materials, the production of the product to the disposal of the product after use. As a mature management tool, life cycle assessment (LCA) has been widely used in the research of meat production by domestic and foreign scholars [3]. This article will discuss the production process of plant-based meat substitutes, using Life Cycle Assessment (LCA) to emphatically compare the environmental impacts (greenhouse gas emissions, energy use, water footprint, land use) of pork production and plant-based meat substitute production. Finally, this article will present the current challenges faced by the development of plant-based meat substitutes, such as low consumer acceptance of plant-based meat substitutes, and provide some solutions to address these challenges.

2. Definition and Production Process of Plant-Based Artificial Meat

2.1 Definition

Plant-based artificial meat is an alternative food made from plant materials and processed with modern food technology to simulate the taste, flavor, texture and nutritional characteristics of animal meat.Plant-based artificial meat and cell-cultured meat products are designed to use non-animal-derived materials to simulate and restore the eating experience of traditional animal meat products, so as to meet consumers' dietary needs for meat and reduce dependence on traditional animal husbandry [4]. This will achieve the goals of energy conservation and emission reduction, animal protection, healthy diet, and responding to food crises.However, compared to cultured meat from cells, plant-based artificial meat mainly uses plant proteins such as soybeans, peas, and wheat as its raw materials, along with various additives including water, fat, polysaccharides, flavoring agents, and colorants,The technology of reorganizing plant protein into a meat-like structure through scientific processing is more mature and the cost is lower.

2.2 Production Process

The production process for plant-based meat alternatives involves: Raw material selection→Raw material pretreatment→Protein extraction and separation→Protein processing and conditioning→Ingredient blending→Forming and processing→Flavor and color formulation→Shaping and packaging→Sterilization and quality inspection.In order to make plant protein have a meat-like texture and taste, extrusion technology, spinning technology and 3D bioprinting technology are used for organization processing in the molding process [5].

Extrusion technology is the most common structured process for converting plant proteins into fibrous extrudates. Depending on the moisture content of the raw materials, extrusion technology can be divided into low-moisture extrusion (moisture content 20-40%) and high-moisture extrusion (moisture content 40-80%).Low-moisture extruded products offer advantages such as high flexibility and ease of storage. In contrast, high-moisture extruded products exhibit fibrous structures and textural characteristics similar to meat [6].

Spinning technology is more often used to imitate meat products with finer fiber structures, such as high-end steaks, chicken breasts, etc.The advantage of 3D bioprinting technology lies in its ability to replicate the marbling pattern of meat.

To achieve a texture more similar to animal meat, an enzymatic cross-linking strategy can be employed during the extrusion process to form fibrous structures.

Secondly, to imitate the juiciness and chewiness of meat, fat is an indispensable and high-value food ingredient. The utilization of fat can endow a large number of foods with certain processing properties and sensory characteristics.Therefore, developing meat fat analogues—such as indirectly structuring plant-based liquid oils via emulsion templates, structuring plant-based liquid oils using gelling agents (oil gelation), and structured emulsions—holds significant importance for enhancing the overall performance of plant-based meat [7].

3. The Different Environmental Impacts of Plant-based Artificial Meat and Pork

LCA, as a well-established tool for environmental management, has been widely applied by scholars both at home and abroad in the environmental studies of various production sectors, including meat production.This section uses LCA, selects the cradle-to-grave system boundary, and uses 1 kg of edible protein as the functional unit to compare the environmental impacts of plant-based artificial meat and traditional pork.Data primarily originates from the Ecoinvent database and domestic Chinese agricultural and food processing research (such as the China Life Cycle Database (CLCD)). Key indicators include greenhouse gas emissions (kg CO2eq), energy consumption (MJ), water footprint (m^3), and land use ($m^2 \cdot a$). The analysis shows that the environmental impact of plant-based artificial meat is significantly lower than that of pork.

3.1 Greenhouse Gas Emissions

Global climate change is a prominent environmental challenge to human survival and development and the security of the earth. It threatens food and water security, endangers human health, increases the probability of human infection with respiratory diseases and infectious diseases, aggravates air pollution, disrupts the balance of the natural environment and ecosystems, and leads to the loss of biodiversity. Greenhouse gas emissions are the primary driver of global climate change. The food system—encompassing all elements and activities related to food production, processing, distribution, preparation, and consumption—contributes to 34% of global greenhouse gas emissions at the planetary scale due to emissions occurring throughout its various stages. It has thus become one of the most significant drivers of global climate change [8,9]. Food comes from various plant and animal-derived products. Due to the differences in the physiological characteristics of crops and livestock, as well as the variations in management measures during agricultural production, there are significant differences in the greenhouse gas emissions of the two.On average, plant protein emits 1.2-1.8 kg CO2eq of greenhouse gases, while pork emits 6.5-7.5 kg CO2eq of greenhouse gases.Overall, plant-based meat systems reduce CO2eq emissions by 89% compared to animal meat systems.The lower cumulative energy demand (CED) of the plant-based system and the additional emissions involved in pork production, such as feed cultivation, intestinal fermentation (CH4), and manure management (N2O), can largely explain this result.

3.2 Energy Consumption

Energy consumption is a major pillar of environmental sustainability. Reducing energy consumption can effectively reduce the emission of greenhouse gases and air pollutants, thereby slowing climate change, stabilizing global climate patterns, and reducing the risk of species extinction.

The energy consumption associated with plant protein production is typically significantly lower than that of animal protein. Compared to animal protein, plant protein production requires less water and land resources while achieving higher protein conversion efficiency.The main reason lies in the trophic level efficiency of energy conversion.In the process of energy being transferred from the sun to the plant‘s herbivores and then to the carnivores, only about 10% of the energy is effectively transferred to the next level.Thisnn implies that animal production is inherently a „high-loss“ energy conversion process. The production of plant-based protein products is relatively straightforward, directly extracting protein from plants. This approach reduces the resources and energy required for raising and converting animals, meaning plant-based processing consumes only 0.15–0.2 kg oil equivalent.The production of animal protein, on the other hand, requires a large amount of feed and a longer growth period. For instance, it takes 5 grams of plant protein to convert into 1 gram of animal meat, while 1.5 grams of plant protein can be converted into 1 gram of plant protein meat.In addition, a large amount of energy is still consumed during product processing, temperature control and transportation. The production of pork requires 0.9-1.0kg oil eq, which is 5 times that of plant-based pork.

3.3 Water Footprint

The extraction, treatment, and transportation of water resources all consume significant amounts of energy. Reducing water usage indirectly decreases this energy consumption and associated carbon emissions.In addition, water footprint has a direct connection with freshwater ecosystems. Reducing water footprint can effectively prevent problems such as declining groundwater levels, river dry-up and lake shrinkage, and provide living space for

ISSN 2959-409X

species such as fish, amphibians and water birds, thereby maintaining the health of wetland ecosystems.

The water footprint of plant-based proteins is usually much lower than that of animal-based proteins.Producing one kilogram of traditional pork requires approximately 2,211 to 4,460 liters of water, while producing one kilogram of plant-based artificial pork requires only about 800 liters of water. This means the water footprint of plant-based meat production is just one-eighth that of traditional meat.The core reason is that animal protein production requires large amounts of fresh water for drinking water, feed crop cultivation (green water and blue water), and manure management during the farming process (increasing the grey water footprint).At the same time, converting plants into animal protein results in energy loss, leading to an increase in the total amount of water resources required to produce the same amount of protein.Plants themselves require relatively little water to sustain growth, primarily relying on rainfall and irrigation water. Plant-based foods extract protein directly from plants, thereby avoiding the massive water consumption and pollution associated with animal husbandry.

3.4 Land Use

Land use change is one of the main ways in which humans affect the environment. Improper land use can disrupt the balance of natural ecosystems and lead to a series of chain environmental problems, including loss of biodiversity, intensified climate change, water shortages and pollution.

Using „per kilogram of raw ground pork produced" as the functional unit, pork production requires approximately 6.0–7.0 m² crop equivalent per kilogram of land resources, whereas plant-based artificial meat requires only 2.0–2.2 m² crop equivalent per kilogram, reducing land use by approximately 60%.This is mainly because the livestock industry requires a large amount of land for pasture and the cultivation of feed crops, while plant-based production directly utilizes crop raw materials and skips the energy conversion rate-limited animal breeding process.This efficient land use means that deforestation and natural habitat destruction can be significantly reduced, making a significant contribution to protecting biodiversity, mitigating climate change, and reducing the environmental pressures of agricultural expansion.

4. Consumer Acceptance and Flavor Technology Improvement

Many consumers have reported that plant-based artificial meat has flavors such as beaniness, grassiness and bitterness, etc. Therefore, flavor improvement is the core technical challenge that determines the acceptance of consumers [10].The key to solving this problem lies in masking undesirable flavors and building traditional animal meat flavors.There are currently two main methods to reduce unpleasant flavors: one is to remove the fishy smell from the source raw materials, such as enzymatic hydrolysis and fermentation treatment.Reducing bean odor by selectively inactivating fat oxygenases and lipases to minimize the formation of off-flavor aldehydes such as hexanal, followed by fermenting soybean meal with Aspergillus oryzae or lactic acid bacteria to degrade oligosaccharides and phytate, thereby enhancing flavor purity [11,12].The second is odor masking technology [13]. Adding seasonings to plant-based meat products can mask odors and simulate the flavor of meat, such as natural spices such as basil and fennel.To achieve traditional animal meat flavor profiles, three key approaches can be employed: enhancing the Maillard reaction (by adding cysteine/ribose), introducing genetically engineered heme to catalyze lipid oxidation for aroma development, and utilizing yeast extracts, hydrolyzed plant proteins, and nucleotides to boost umami. These strategies ensure plant-based meat closely mimics the savory taste of animal meat, thereby enhancing overall consumer acceptance [14].

5. Policy Support and Industry Promotion Path

To promote the development of the plant-based meat industry and help achieve the goal of carbon neutrality, the government has introduced a series of policies.In terms of financial and tax incentives, value-added tax reductions and corporate income tax preferences will be implemented for agricultural product processing enterprises, and equipment investment subsidies will be provided.The green certification system is gradually improving, with enterprises in some regions having obtained carbon neutrality certification and established carbon footprint accounting standards for plant-based meat.In terms of public procurement, institutions such as schools and hospitals have begun to adopt plant-based meat products.Financial support policies include low-interest loans and carbon finance innovation, providing interest-subsidized loans to relevant companies to help incorporate future emission reduction benefits into carbon trading.These multidimensional policies—encompassing taxation, certification, procurement, and finance—have created a favorable development environment for the plant-based meat industry by establishing low-carbon standards, developing stable markets, and guiding long-term investment.There is currently a lack of unified national standards for plant-based artificial meat. In the future, governments of various countries should promote the formulation of relevant technical specifications, labeling systems and testing method.

6. Conclusion

Against the backdrop of traditional animal husbandry facing multiple pressures such as resource constraints, environmental pollution, and greenhouse gas emissions, plant-based meat demonstrates significant environmental advantages and sustainable development potential. A systematic life cycle assessment shows that the plant-based meat substitutes can reduce greenhouse gas emissions by approximately 89%, lower energy consumption by 80%, and enhance land use efficiency by 60% per functional unit during the production process. This excellent environmental performance is primarily attributed to its avoidance of high-pressure links in traditional animal husbandry, such as feed cultivation, animal rearing, and manure management, which significantly reduces the overall resource demand and ecological burden of the entire production system. However, consumer acceptance remains a key challenge in promoting plant-based meat, requiring comprehensive measures such as technological improvements, taste optimization, nutritional enhancement, and policy support to address it. Overall, plant-based meat not only has the potential to meet future meat demand but also contributes to global sustainable development goals, serving as a vital pathway to alleviate environmental pressures and resource constraints. In the future, it is imperative to advance the standardization, large-scale production, and nutritional functionalization of plant-based meat products. Coupled with consumer education, policy incentives, and technological innovation, these efforts will foster the development of a more market-competitive and socially endorsed industrial ecosystem for plant-based meat alternatives.

Authors Contribution
All the authors contributed equally and their names were listed in alphabetical order.

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