Dean&Francis
ISSN 2959-409X

Optimization of the Flavor Simulation Technology for Plant-based Meat

Yuchen Han[1, *]

[1]Westa College Southwest University, Chongqing,400715, China
*Corresponding author: rasmus1125@163.com

Abstract:
Amid a growing global demand for protein, traditional animal meat is increasingly struggling to keep up, burdened by three main constraints: limited resources, rising environmental concerns, and ethical issues related to animal welfare in industrial farming. This gap has driven plant-based meat (PBM) to become a popular sustainable alternative. However, PBM technology is still in development and faces significant challenges. Flavor-wise, legume-based ingredients often add an unwanted beany taste; texturally, they find it hard to mimic the chewiness of real meat; and visually, they lack the appealing pink color of raw animal meat. Nutritionally, PBM also has shortcomings, including a lack of essential amino acids and insufficient vitamin B12. Based on current research, this review suggests several possible improvements: selecting the best raw materials, utilizing enzymatic treatments to enhance flavor, employing leghemoglobin and edible pigments to improve color, and adding essential nutrients to strengthen nutritional value. It also highlights the need to increase consumer acceptance and explore future opportunities to advance PBM.

Keywords: Plant-based meat; Flavor & color simulation; Leghemoglobin; Nutritional balance.

1. Introduction

In recent years, as living standards have risen, meat consumption has steadily grown each year. The Food and Agriculture Organization of the United Nations predicts that by 2050, meat demand will increase by 70% compared to current levels.

The core advantages lie in PBM, which significantly reduces natural resource consumption at the environmental level by utilizing modern food processing technology that mimics the texture and flavor of meat, thereby simulating its taste. Plant proteins, such as soy protein, pea protein, and wheat protein, are the primary raw materials for producing PBM. Proteins typically undergo stages of hydration, denaturation, cross-linking, etc., during extrusion processing [1]. The main obstacles in PBM are the poor sensory experience, the Lack of nutrients, and the high cost of production. The issues in sensory perception, especially in terms of flavor, are in urgent need of resolution. Since there are few systematic sorting and analysis of current challenges and solutions. There-

ISSN 2959-409X

fore, this review will focus on enhancing flavor simulation technology for PBM, addressing color and nutritional composition as a supplement.

2. Challenges of Flavor

PBM faces specific flavor challenges that impede its sensory resemblance to traditional meat. A primary concern is the presence of undesirable off-flavor, including beany tastes, bitterness, and astringency, which are especially noticeable in legume proteins like soy and pea [2]. These off-flavors originate from lipid oxidation reactions caused by enzymes like lipoxygenase (LOX), which break down polyunsaturated fatty acids into volatile compounds—hexanal, for example, is a major contributor to the beany flavor [3,4].

Another important gap is the sensory appeal, which is lacking due to the absence of animal fat. In traditional meat, fat not only contributes the soft, juicy texture but also releases aromatic compounds when cooked, boosting overall flavor. Without this fat component, plant-based meat often dry or tough, and plant oils do not imitate the complex flavor-release process of animal fats during cooking, resulting in a noticeable sensory mismatch [5].

3. Strategies for Flavor Challenges

3.1 Selection of Raw Material

3.1.1 Bean protein

In the commercial market, leading brands have adopted targeted approaches: Beyond Meat uses a blend of pea, brown rice, fava bean, and mung bean proteins, while Impossible Foods relies primarily on soy protein [5]. Additionally, Impossible Foods includes soy hemoglobin, a protein that mimics meat's bloody look and boosts meat-like flavor through reactions during heating. These options aim to strike a balance between functionality and taste.

As seen in Figure 1, soy protein has become the main raw material due to its excellent gelation properties, potential for fiber structure formation, balanced nutritional value, and low cost [1]. However, it has problems such as flatulence factors, anti-nutritional factors, and a beany flavor. Pea protein is less allergenic and helps stabilize structure, but its structure is vulnerable to damage during extreme processing and has weak gelation ability. Therefore, by combining proteins, such as soy with wheat, peas, and others, the shortcomings of individual raw materials can be mitigated, leading to an improved nutritional balance and enhanced structural stability.

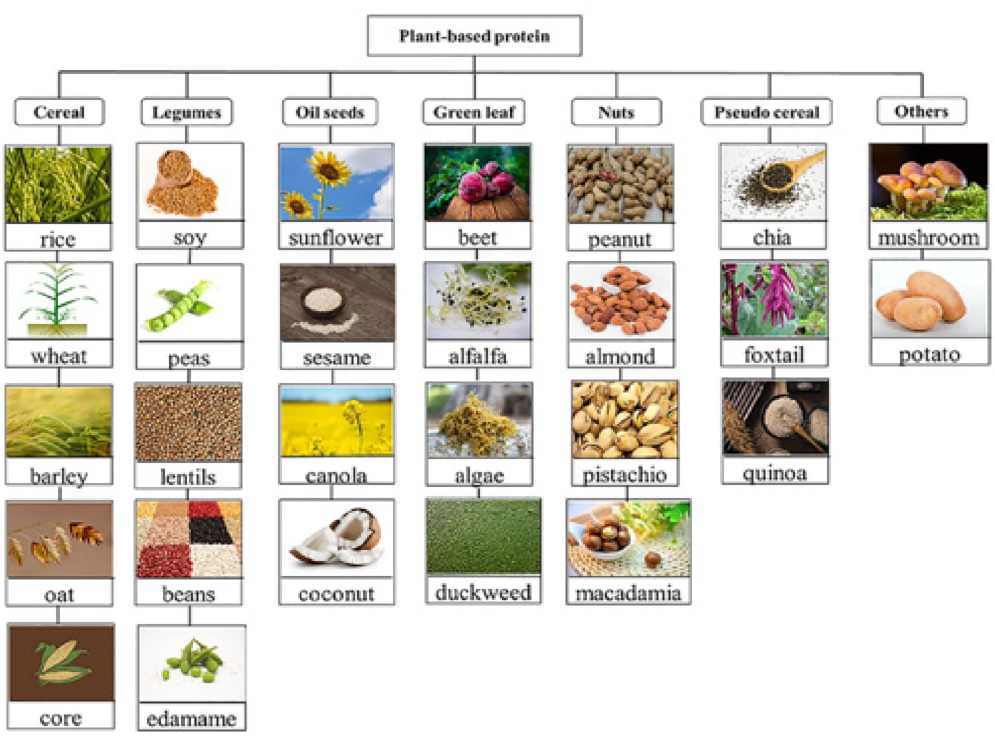

Fig. 3. Main plant protein sources (HADIDI M, et al 2022).

Fig.1 Main plant protein sources [2]

3.1.2 Fungal protein

From Figure 1, it can be easily found that another innovative source of plant proteins is fungal protein meat analogs, which offer significant advantages. They are nutritionally rich, with 100g of dried fungal protein containing 45g of protein and other components. The biological value of the protein is equivalent to that of milk; the content of Vitamin B is higher than that of meat, and they are rich in umami components. Dietary fiber and polyunsaturated fatty acids are beneficial to health. The water consumption and land occupation for production are approximately 1/20 and 1/23 of those for traditional meat, making them more environmentally friendly. The production process is straightforward, can be carried out through various fermentation systems, and utilizes low-cost substrates. There are already commercial cases, and they can reduce the risk of food-borne diseases [4]. Nucleic acids present in fungal protein meat can cause metabolic diseases such as gout if consumed excessively. Common removal techniques include ultrasonic disruption, the concentrated salt method, a combination of salt and ultrasonic treatment, and bacterial autolysis. However, a gap remains before reaching a level suitable for human consumption. To use microbial proteins as the main ingredient, it is essential to develop edible fungal strains capable of high protein yields and to establish scalable production methods and processing techniques for edible fungal proteins [5].

3.2 The Mechanism and Removal of Off-flavor Formation

3.2.1 Mechanism

The beany flavor of soy protein plant-based meat is produced synergistically by volatile compounds such as aldehydes (e.g., hexanal, a key flavor component), alcohols (e.g., 1-octen-3-ol), ketones, and furans. These substances bind to soy protein through hydrogen bonds, hydrophobic interactions, and other means, and are released during processing and consumption to activate olfactory receptors.

Its formation is primarily closely related to the extrusion process. On one hand, residual lipids in raw materials and added oils undergo lipid oxidation under high temperature, high pressure, and high shear conditions. Unsaturated fatty acids (such as linoleic acid and linolenic acid) are oxidatively degraded to produce hydroperoxides, which are further broken down into off-flavor compounds like aldehydes, ketones, and furans. This process is influenced by the composition and amounts of fatty acids as well as the extrusion temperature. On the other hand, the high temperature during extrusion encourages the Maillard reaction between amino acids from soy protein degradation and reducing sugars. The intermediate products react with free amino acids through Strecker degradation to form aldehydes (e.g., alanine produces acetaldehyde), which worsens the beany flavor [4].

3.2.2 Biological & physical methods

Biological methods mainly decrease beany substances through biotransformation or enzymatic hydrolysis. First, fermentation technology uses the metabolic activities of specific microorganisms, such as Saccharomyces cerevisiae SK 1.008 and Lactobacillus plantarum FSB7, to break down beany precursor substances (like unsaturated fatty acids and sulfur-containing amino acids) in soybean protein. At the same time, flavor compounds such as organic acids, esters, and alcohols are produced to mask or neutralize the beany flavor. Second, enzyme preparations inhibit the activity of key enzymes involved in lipid oxidation by adding lipoxygenase inhibitors, thereby reducing the oxidation of unsaturated fatty acids like linoleic and linolenic acids that can produce fishy substances like hexanal. Alternatively, using phospholipase combined with α-cyclodextrin can effectively remove the beany flavor [2]. Heat treatment of legumes can substantially lower their LOX activity, which in turn minimizes the formation of flavor compound products in legumes. The radio frequency (RF) heating is highly efficient and uniform. The advantages of RF energy are that it can penetrate the interior of food, allowing it to be heated evenly throughout. This minimizes large temperature differences between the inside and outside during traditional heating, preventing local overheating or underheating. It is especially useful for large pieces of food with high moisture content. It can also effectively preserve the color, texture, and nutritional content of the food. When RF heating is applied for 210 seconds, LOX experiences an inactivation rate of 94.30%. Additionally, some volatile compounds produced during heat treatment, such as pyrazines and alkylated pyridopyrimidines, have a masking effect on bean flavor [2].

3.2.3 Addition of flavorings

Various flavor substances are often added to plant-based meat to improve its taste, including Maillard reaction products and yeast extracts, which deliver a strong meaty flavor, reduce bitterness, and mask off-flavors in the production of PBM [2]. Additionally, the flavor of plant-based meat products can be improved by incorporating flavoring ingredients and binders. Natural spices, such as garlic, onion, basil, and pepper, are high in antioxidants, which help inhibit lipid oxidation reactions and reduce the development of bean-like textures [4]. Furthermore,

ISSN 2959-409X

adding 2% to 5% fat to artificial meat can better enhance the product‘s flavor. However, adding too much fat may easily affect the tissue structure of the product, causing its compactness to decline. Furthermore, coconut flesh and konjac gel can be mixed to mimic fat and incorporated into artificial meat.

4. Challenges of Color

The plant-based meat products mainly face two issues related to color. First, their color is quite different from that of real meat. They often appear light brown or gray, with a fine texture, and lack the bright red hue and marbling pattern of real meat, which can influence consumers‘ initial impressions and purchasing choices. Second, their color stability is poor. During processing and storage, they tend to brown, making it hard to keep the ideal color and posing challenges for shelf life and sales.

5. Strategies for Color Challenges

5.1 Heme

In plant-based meats, soy‘s leghemoglobin (LegH), a close structural ortholog of myoglobin, serves a similar crucial function. While LegH‘s amino acid sequence varies greatly from animal hemoglobin and myoglobin, its three-dimensional structure remains highly similar, so it is the most popular way to mimic the color of meat [6]. Additionally, consuming too much heme from animal products is associated with an increased risk of type 2 diabetes, cardiovascular disease, and stroke. Currently, Impossible Foods has developed a commercial Pichia pastoris strain and filed a patent for it. This strain can efficiently produce Soy leghemoglobin using the methanol-induced promoter PAOX1, which not only provides a color similar to that of meat but also boosts the flavor of PBM. During heat treatment, soy leghemoglobin denatures, causing its structure to unfold and exposing heme. This heme can catalyze reactions with plant-derived biomolecules in the ingredients, producing a flavor and aroma similar to heated meat [3].

5.2 Other Pigments

Beyond Meat’s burgers mainly employ beet juice extract, carmine orange, and vitamin C to achieve a consistent, stable color. The red from beet juice and the yellow from carmine orange blend to form a reddish-brown shade in baked meat pies, similar to traditional beef varieties. Vitamin C contributes by creating reducing and acidic conditions that help prevent the oxidation of betacyanin in beet juice [2].

6. Challenges of PBM from a Nutritional Perspective and Strategies

From a nutritional standpoint, compared to animal protein, plant protein has lower saturated fat content, no cholesterol, and is high in dietary fiber [7]. It helps reduce the risk of cardiovascular diseases and promotes better intestinal health [8]. However, it has some challenges.

6.1 Shortage of EAA

The amino acid composition of pea protein is close to the human body‘s requirements. It contains eight essential amino acids and is rich in branched-chain amino acids that are beneficial for muscle growth and repair. However, it has less methionine and tryptophan. The protein content of pea protein is 20%-25%, and its amino acid profile is similar to that of animal protein, rich in lysine and branched-chain amino acids. Moreover, it has higher contents of methionine and tryptophan, which can supplement the deficiency of soy protein. Hence, an effective strategy to solve the EAA deficiency is to use a mixture of plant proteins, which is also the most widely applied method [2]. Recent research findings have utilized mathematical models as an innovative technology to optimize the ratio of amino acids in PBM products. To be more specific, it aims to create an amino acid profile for the mixed proteins that is similar to that of a given animal source, which has great application prospects.

6.2 Shortage of Vitamin B12

Vitamin B12 is a complex compound containing cobalt, also known as cobalamin. It is a necessary trace nutrient for the human body, but cannot be synthesized internally, so it must be obtained from external sources. The primary source of vitamin B12 is almost exclusively found in animal-based foods such as meat, fish, eggs, and dairy products. Plant-based foods generally do not contain it. A deficiency in vitamin B12 can affect the blood system, causing megaloblastic anemia, and can also damage the nervous system. Therefore, it is vital to add vitamin B12 to PBM. Currently, the most common method is to include it in a premix with plant-based meat. However, domestic research in this area is limited, especially regarding the effects of protein form, time, and temperature on vitamin B12 content in PBM.

7. Conclusion

This review analyzes and summarizes the main challenges of PBM in terms of flavor, color, and nutrition. It discusses methods to reduce beany flavor, simulate color with heme, and balance nutritional content. It also introduces innovative technologies that utilize mathematical models to optimize the nutritional composition, thereby enhancing the taste and nutritional profile of plant-based meat. However, due to limited research and literature, this review lacks an in-depth analysis of the impact of time-temperature interaction on vitamin B12 in the PBM matrix.

Up to now, the market scale of China's plant-based meat industry reached 14.27 billion yuan in 2023, demonstrating substantial development potential in this field; enterprises such as Shenzhen Starfield Food Technology Co., Ltd. have continuously pursued innovation by launching a variety of plant-based meat products to enrich market offerings, while Nanjing Zhouzi Future Food Technology Co., Ltd., having collaborated with Nanjing Agricultural University on plant-based meat technology research since 2009, achieved the world's first pilot-scale (500L) mass production of plant-based meat in 2023 which completing the leap from hectoliter-scale reactor trial production using seed raw materials to pilot-scale mass production, yielding kilogram-level plant-based meat per week of operation. Its related technological achievements have also passed scientific and technological achievement evaluation, with the overall technology reaching an internationally leading level; breakthroughs have been made in raw material ratio optimization, flavor simulation, and mass production processes, including a 40% increase in core raw material utilization rate and a 5-fold improvement in production efficiency, which have significantly reduced the production cost of plant-based meat. Looking forward, efforts need to address various technological, standard, market, and industrial areas. Technologically, the emphasis should be on odor control, color stability, vitamin B12 retention, and the development of functional products. In terms of standards, establishing a comprehensive chain of custody standard system and a traceability framework is essential. Market-wise, competitiveness can be boosted through consumer education, cost reduction by optimizing equipment energy use and scaling up fungal protein production, and by creating region-specific flavors. Industrially, encouraging collaboration and partnerships between industry, universities, and research institutions will help PBM become a more popular food choice, easing protein supply challenges and conserving resources.

Ultimately, as simulation technology advances and standards mature, PBM is expected to become mainstream, thereby contributing to sustainable development and promoting healthy diets.

References

[1] Wang Y, Lyu B, Fu H, Li J, Ji L, Gong H, Zhang R, Liu J, Yu H. The development process of plant-based meat alternatives: Raw material formulations and processing strategies. Food Res Int. 2023 May;167:112689.

[2] Su T, Le B, Zhang W, Bak KH, Soladoye PO, Zhao Z, Zhao Y, Fu Y, Wu W. Technological challenges and future perspectives of plant-based meat analogues: From the viewpoint of proteins. Food Res Int. 2024 Jun;186:114351.

[3] Zhao Jiuyi, Zhou Ruili, Qiao Cuihong. Progress in Improving the Quality of Plant-Based Artificial Meat [J]. The Food Industry,2025,46(06):199-204.

[4] Deng Zimeng, Liu Sidi, Zhao Jing, LAO Fei, YANG Dong, ZHAO Liang, LIAO Xiaojun. Research Progress on Formation and Removal of Beany Flavor in Soy Protein-Based Meat Alternatives [J/OL]. Science and Technology of Food Industry,1-18[2025-08-13].

[5] Zhang Zhixia, Ma Xinmiao, Xu Hui, et al. Research Status and Prospects of Artificial Meat Technology [J]. Science and Technology of Food Industry,2024,45(17):416-425.

[6] Fraser RZ, Shitut M, Agrawal P, Mendes O, Klapholz S. Safety Evaluation of Soy Leghemoglobin Protein Preparation Derived From Pichia pastoris, Intended for Use as a Flavor Catalyst in Plant-Based Meat. Int J Toxicol. 2018 May/Jun;37(3):241-262.

[7] Fu Xiaohang, Zhang Shunliang, Zhao Yan ,et al. Research Progress on Nutrition and Safety of Plant-Based Meat [J/OL]. Food Science,1-14[2025-08-15].

[8] Hua XY, Long Y, Ong DSM, Theng AHP, Shi JK, Osen R, Wu M, Chiang JH. Mathematical optimisation of extruded mixed plant protein-based meat analogues based on amino acid compositions. Curr Res Food Sci. 2023 Dec 5;7:100648.