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# Processing, Quality, Safety, and Acceptance of Meat Analogue Products

Cuixia Sun [a], Jiao Ge [a], Jun He [a], Renyou Gan [b], Yapeng Fang [a,*]

[a] Department of Food Science and Engineering, School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Institute of Urban Agriculture, Chinese Academy of Agricultural Sciences, Chengdu 610213, China

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ABSTRACT

Rapid global population growth has caused an increasing need for products containing protein. Meat products are the most common high-protein food source, but impact the environment, cause animal welfare issues, and raise public health concerns. Consumer health and food safety are paramount to the food industry. Both the scientists and food industry are actively seeking plant proteins to substitute for animal-sourced proteins. Plant proteins have a well-balanced amino acid composition, and exhibit great potential for replacing meat via the development of healthy, high-protein, low-saturated fat, cholesterol-free, and nutritionally similar meat-like products. Generally, meat analogue formulations are specially designed and processing conditions are optimized to obtain the texture and bite of real animal meat. This article focuses on plant-based meat analogues, and covers aspects regarding processing, products, quality, and nutritional and structural modifications. Product safety consciousness and consumer acceptance are also discussed. Challenges and perspectives for future research concerning nonmeat products are presented.



## 1. Introduction

Proteins are an essential component of human nutrition. Protein supply is nutritionally and environmentally crucial. Meat, as a main source of high-quality proteins, has been widely consumed by humans. However, livestock animals are reared for meat production, during which enormous land and water resources are used, leading to an increase in greenhouse gas emissions and a severe environmental impact [1–3]. Food borne pathogens are frequently found in meats and are responsible for millions of illnesses [4]. Additionally, the intake of red meat can cause ischemic heart disease, worsen the obesity epidemic, and increase the risk of joint inflammation [5] and colorectal cancer [6]. Therefore, more people prefer to eat less meat or completely exclude it from their diets for health reasons. To reduce environmental issues, alleviate public health concerns, and make food production sustainable, alternatives to conventional animal products are being created. Alternative animal products have many common terms, including meat analogues, meat substitutes, meat imitations, meat replacements, meat replacers, imitation meat, mock meat, meatless meat, faux meat, and mimic animal meat. The term "meat analogue" refers to meat-free food products that have a similar taste, haptic experience, appearance, and nutritional value to traditional meat products [7,8]. The results from a life cycle assessment show that meat analogues have considerably lower greenhouse gas emissions and can therefore provide environmentally advantageous alternatives to animal-derived meat [9]. Based on their origins, meat analogues can be classified into two major types: cultured meat and plant-based meat analogues. Cultured meat is described as "synthetic," "*in vitro*," "artificial," "laboratory-grown," or "factory-grown" meat and produced via the culture of animal stem cells into muscle cells that further develop into tissue [10,11]. Cultured meat is grown in clean and controlled environments, and thus is guaranteed to be free of bovine spongiform encephalopathy and foot-and-mouth disease. Sergey Brin, the founder of Google in the United States, provided funding for research using beef stem cells to grow artificial meat at the University of Maastricht. However, this research is still in the laboratory stage. Furthermore, it costs approximately 10 000 USD to produce a kilogram of "artificial meat," which is more than 1000 times the price of conventional meat in the retail market. Cell culture is regarded as inefficient in terms of energy, water, and feedstock expenditure. Such artificially cultured meats have a low consumer acceptance because of the limited knowledge regarding the biology

* Corresponding author.
*E-mail address:* ypfang@sjtu.edu.cn (Y. Fang).

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of stem cells [12,13]. Plant-based meat products are foods mainly composed of proteins of plant origin. In recent years, as a kind of healthy and exotic food product, there has been increasing interest in premium plant-based meat analogues among consumers. Plant-based meat analogues are particularly popular in industrialized countries. In this review, we focus on the quality, processing, and safety technology of plant-based meat substitutes.

## 2. Sources and products

Proteins are a valuable food component for growing and maintaining human body functions. Regarding human protein nutrition, there are a wide variety of sources: cereal grains, such as wheat, rice, maize, and barely; oilseeds, such as canola and rapeseed; and food legumes, such as soybeans, peas, and chickpeas [14,15]. The different physicochemical, structural, and functional characteristics depend upon the different protein types. Major protein ingredients currently applied in the production of meat alternatives are soy protein, wheat gluten, and pea protein [16]. Soy protein, including soy protein isolate and soy protein concentrate, is the dominant ingredient in structured plant protein products because of its abundance, low-cost, meat-like texture after hydration, and high-quality amino acid composition, which provides a similar protein quality to that of animal proteins [17,18]. Soy protein also plays a potential role in preventing cardiovascular disease. For instance, the Food and Drug Administration approved a health claim that 25 g of soy protein a day may lower cholesterol and reduce the risk of coronary heart disease [19]. Soy-based meat analogues not only have high protein levels and equivalent nutritional values to meat, but also contain little or no cholesterol and fat because of the incorporation of optional components [20]. However, soy proteins have many drawbacks due to their antinutritional factors and allergenic potential [21]. As a type of large disulfide-linked protein assembly, wheat gluten has historically been the predominant base ingredient utilized in the production of meat analogues because it can form a three-dimensional network. This helps to form a successful association and provides the essential consistency in meat analogue products [22,23]. Wheat allergy, as one of the most common causes of food allergies in children, usually begins in early childhood [24]. Pea protein is the most promising for the application of meat analogues because of its low allergy, high nutritional value, and great emulsion and foam stabilization abilities [25]. Pea-based structures are considerably softer and less elastic than those of soy-based products because of their weaker gelling capacity [26]. It should be mentioned that although plant proteins are good protein sources, many of them lack one or more of the essential amino acids. Therefore, the presence of additional protein sources, such as whey proteins and egg whites, is encouraged in meat analogue production, for both nutrition and functional purposes [27].

It is a well-known fact that the function and nutrition of individual proteins are limited, and a synergistic effect can be achieved by combining them with other ingredients. That is, the quality of meat analogues is dependent upon the sample composition. The addition of wheat gluten in analogue meat nuggets improves almost all sensory traits [28,29]. Soy fiber incorporation (5%–10%) results in a more directional and finer texture of meat substitutes [30]. Iota carrageenan (ICGN) has a great ability to retain moisture. The addition of ICGN improves textural properties, and the increase in the ICGN concentration leads to more fibrous and less juicy products, with improved overall acceptance. In a previous study, soy protein meat analogues with 1.5% ICGN were best liked by the panelists [31]. Furthermore, adding vitamins (vitamin B12) and trace elements (iron and calcium) to meat analogue recipes may further contribute to a healthy diet, particularly a pure vegan diet, significantly improving consumer acceptance. It should be mentioned that refinement, such as marinating, tumbling, smoking, bread coating, stuffing, frying, and grilling, would affect the nutritional value of plant-based meat analogues. However, these steps are necessary, as it is crucial to transfer the base ingredients to well-accepted food products. Thus, they are an important aspect of consumer acceptance [32,33]. Compared to ground beef, meat analogues have higher polyunsaturated fatty acids, potassium, calcium, and phosphorous, with negligible changes in biological value after home cooking [34].

Plant-based meat analogues are typically cut to a specific shape, with the desired sizes of commercial products in the market ranging from 6 to 20 mm [35]. Companies that have relatively mature processing skills for plant-based meat products are emerging, such as Beyond Meat (USA), Vegetarian Butcher (the Netherlands), and Impossible Foods (USA). Beyond Meat, as a typical example, began with Fu-hung Hsieh and Harold Huff conducting plant-based foods research at the University of Missouri. They examined how plant-based meat analogues could be designed to gain more commercial acceptance. Beyond Meat, who started with plant-based grilled chicken-strips, has expanded its products to seasoned ground beef analogs and heritage grain patties. Bill Gates is a fan of Beyond Meat, along with Twitter pioneers Biz Stone and Evan Williams, who all invested in the company. Besides having a similar texture and flavor to real meat, commercial meat analogue products have attractive health benefits. For example, compared to animal-based beef, as shown in Table 1, the antibiotic-free Beyond Burger has higher levels of protein and iron, a lower saturated fat content, and is free of cholesterol [36].

Another noteworthy example is Impossible Foods (USA), whose slogan is "Plants + Science = Meat." Many investors, such as Khosla Ventures, Horizons Ventures, Open Philanthropy Project, and Temasek (which is backed by the Singaporean government), have helped to finance the company. Their team of scientists, farmers, and chefs have identified methods and ingredients that naturally recreate the appearance, aroma, texture, and flavor of ground beef, and successfully created a representative meat analogue product—the Impossible Burger. Compared to a burger made from cow beef, the Impossible Burger contains no cholesterol and has more bioavailable protein (31%), iron (25%), and fat (18%) compared to conventional 80/20 ground beef [37]. All kinds of processed meat substitutes are sold as convenience products in frozen, fresh, pasteurized, and sterilized forms [38]. In the near future, new food products may be developed using these foundations.

## 3. Processing

An early method for producing simulated meat was the fiber spinning technique, which was developed in the 1980s. An alkaline protein solution was extruded through spinnerets into an acidic coagulating base, leading to precipitation into filaments that were assembled into meat analogue products using binding materials [39]. However, the spinning process was complex, needed a highly concentrated plant protein solution, and was very expensive for

**Table 1**
Nutrition facts comparison between the Beyond Burger and animal-based beef.

| Components | Beyond Burger | Animal-based beef |
|---|---|---|
| Protein (g) | 20 | 19 |
| Iron (% DV) | 25 | 12 |
| Saturated fat (g) | 5 | 9 |
| Cholesterol (mg) | 0 | 80 |
| Total fat (g) | 22 | 23 |

Percent daily value (% DV) is how much a nutrient in a single serving of food contributes to human daily diet.

large-scale applications [40]. In recent years, the predominant technique has been the thermal plastic extrusion process. As a well-known approach to producing ready-to-eat breakfast cereals and baby foods in the food industry, extrusion processing has a high productivity and energy efficiency. Generally, plant proteins, typically in a defatted form, are mixed with water, carbohydrates, salts, flavorings, and edible lipid material, before being fed into a twin-screw extruder under a high temperature and different moisture conditions for the formation of a meat-like fibrous structure, as shown in Fig. 1 [41]. To produce desirable products and improve consumer acceptance, meat analogues are designed to infinitely approximate the organoleptic qualities of real meat, such as the texture, taste, flavor, color, and sensation in the mouth, by controlling and optimizing the composition and processing parameters [42]. Meat analogues made via "dry extrusion" (moisture < 30%) have limited acceptance because of their poor mouthfeel. Meanwhile, "wet extrusion" under high moisture conditions (40%–80%) enables the production of fresh and premium meat analogues, with a muscle meat-like texture as well as a similar appearance and chewing sensation to cooked meat [43–45]. The high moisture extrusion (HME) process offers more complex recipes and does not require all ingredients to have a high solubility, leading to a more robust and cost-effective technology [46]. Recently, a simple heated Couette shear cell device has been developed (Fig. 2), in which soy protein suspension and wheat gluten are gelled within linear extensional flows to generate fibrous products [47]. This technique makes it possible to shift from the HME process to the production of simulated textures in the batch process [48]. Furthermore, a shear-induced structuring approach with a high temperature shear cell has been used to form fibrous soy protein structures [49]. A closed cavity rheometer has been developed to alter the thermal and mechanical stresses in a defined manner and at extrusion-like conditions, allowing a small amount of food (approximately 6 g of hydrated wheat gluten) to be processed [50].

## 4. Food safety and consumer acceptance

As previously discussed, consumer health and food safety are paramount to the food industry. Soy foods have traditionally been consumed for more than two thousand years throughout East Asian countries, such as China and Japan, indicating its safety for consumption. Over the last few decades, soybean-derived products have expanded to Western countries and become an economical high-quality vegetable protein source for the human diet [51]. However, studies have also raised concerns that the soy diet may have adverse effects on the cognitive function and mood of humans [52,53].

According to European consumer research, meat analogues find particular acceptance in four main consumer groups: ① consumers reducing their meat consumption and looking for healthy balanced nutrition; ② consumers who are conscious of animal welfare, sustainability, and ethics; ③ convenience-oriented and cost-conscious consumers; and ④ indulgence and innovation-oriented consumers [33,54,55]. Soy formulas are frequently prescribed for adverse reactions to cow milk. However, 10%–14% of patients with a cow milk allergy are also allergic to soy. Enterocolitis and other clinical manifestations of a soy allergy overlap with those of a cow milk allergy [56,57]. Gluten-free protein from maize zein has desirable properties for meat analogue products, can effectively avoid the allergy problem, and is likely to be developed soon.

Additionally, soy-based meat analogues have to face consumer concerns regarding the genetic modification (GM) of soybeans. Although GM technology for modifying the physical and nutritional properties of plant proteins has advanced considerably over the last two decades, some consumers still doubt the potential damage to human health. Heme, an iron-containing molecule, is abundant in animal muscles and responsible for the color and flavor of real meat [58]. As a key ingredient of plant protein-based meat analogue products, such as the Impossible Burger, heme is produced by genetically engineering yeast, briefly adding the soy leghemoglobin gene to a yeast strain, growing the yeast via fermentation, and isolating heme from the yeast [59,60]. The addition of plant-based heme can enhance the intense meaty flavor, aroma, and cooking properties of meat analogues. However, further tests need to be conducted to confirm its safety.

## 5. Challenges

At the macroscopic level, natural meat has muscle fibers that are visually perceptible and have a diameter in the range of microns [61]. The microstructure of imitation meat determines whether the substitute has similar qualities to meat regarding the texture, moisture, and flavor [62]. Generally, the meat substi-

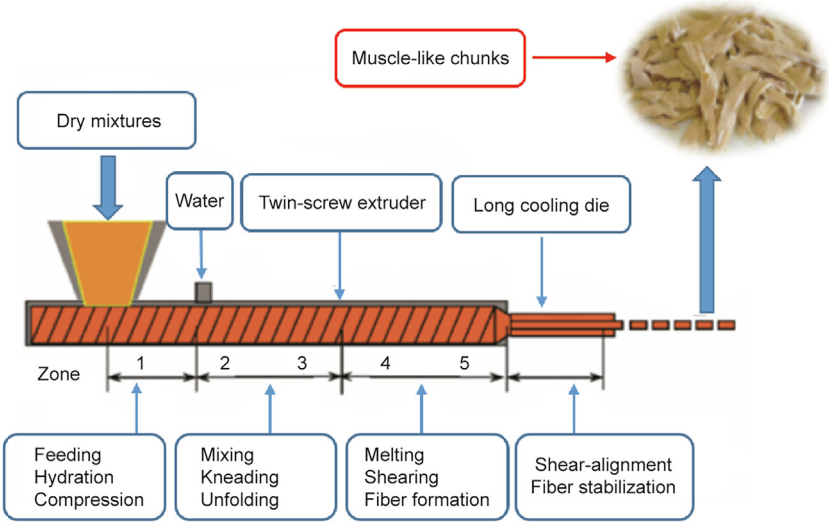


**Fig. 1.** Scheme of a twin-screw extruder for HME of proteinaceous materials into fibrous meat analogues. Reproduced from Ref. [41] with permission of American Chemical Society, ©2008.

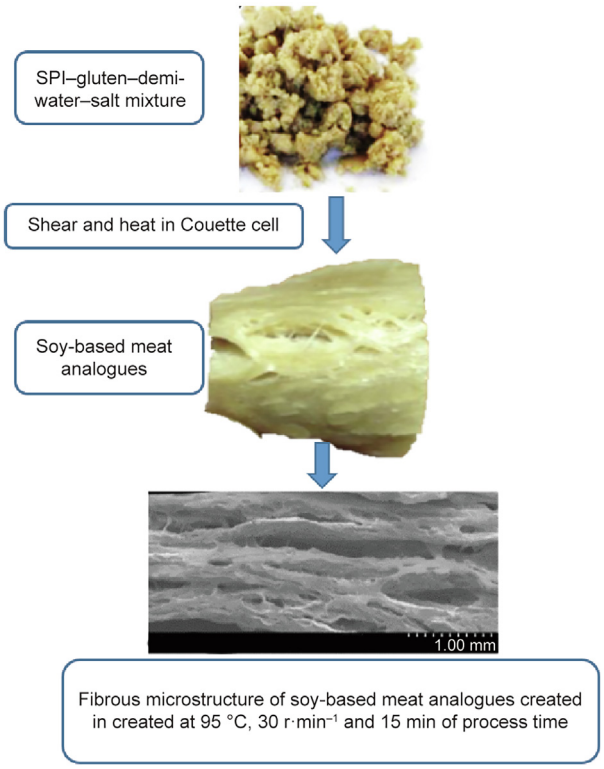


**Fig. 2.** Shear-induced formation of proteinaceous materials into fibrous meat analogues. SPI: soy protein isolate. Reproduced from Ref. [23] with permission of Elsevier Ltd., ©2015.

tute products obtained from the current extrusion process are different from meat because they lack the fibrous structure, bite, and juicy mouth feel of meat. Therefore, the biggest challenge for meat analogue production is to obtain the texture and bite of real animal meat, which may require special designs for meat substitute formulations and the optimization of processing conditions. Seeking more low-cost premium plant protein sources and combinations of selected food ingredients for the preparation of meat-like products is crucial. The current energy-effective extrusion process that allows large-scale production for food retail should be accelerated, and promising techniques for fibrous structuring need to be further developed.

## 6. Perspectives

The development of plant-based meat analogues is believed to be a great way to improve human health, conserve natural resources, and maintain animal welfare. Meat analogues are rich in proteins, vitamins, and minerals, but usually devoid of dietary fiber. As an essential nutritional component for the normal physiological/biochemical process, dietary fiber can be added as a fat replacement in food, which can increase product acceptance. The consumption of dietary fiber can prevent diabetes, irritable bowel disease, and obesity. Therefore, meat analogue products fortified with dietary fiber are received well because of the range of benefits.

Besides nutritional value, many edible components can prevent and cure diseases, which means they fall into the scope of medicine food homology (MFH). More than 80 items have been approved by the National Health Commission of the People's Republic of China to be MFH materials, such as the adzuki bean, white hyacinth bean, Chinese yam, and many kinds of herbal remedies, which can be considered as functional meat replacements

In nanotechnology, the "bottom-up" approach refers to the development of a highly-ordered supramolecular structure via the interaction and self-assembly of simple building blocks. Proteins are capable of self-assembling into fibrils via a nucleation dependent pathway under partially denaturing conditions, such as low pH and heat treatments. Therefore, besides thermal and mechanical treatments like the extrusion process, the "bottom-up" approach could be applied for the engineering of meat analogues. With the increase in the number of options for meat analogue products, we can enjoy delicious healthy meals without inflicting harm on the planet.

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## Compliance with ethics guidelines

Cuixia Sun, Jiao Ge, Jun He, Renyou Gan, and Yapeng Fang declare that they have no conflict of interest or financial conflicts to disclose.

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