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Review

Comprehensive Review on the Role of Plant Protein As a Possible Meat Analogue: Framing the Future of Meat

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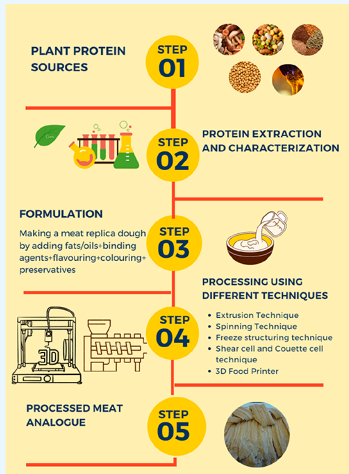
ABSTRACT: Animal proteins from meat and goods derived from meat have recently been one of the primary concerns in the quest for sustainable food production. According to this perspective, there are exciting opportunities to reformulate more sustainably produced meat products that may also have health benefits by partially replacing meat with nonmeat substances high in protein. Considering these pre-existing conditions, this review critically summarizes recent findings on extenders from a variety of sources, including pulses, plant-based ingredients, plant byproducts, and unconventional sources. It views these findings as a valuable opportunity to improve the technological profile and functional quality of meat, with a focus on their ability to affect the sustainability of meat products. As a result, meat substitutes like plant-based meat analogues (PBMAs), meat made from fungi, and cultured meat are being offered to encourage sustainability.



1. INTRODUCTION

The world's food systems will need to feed a population of more than 10 billion until 2050, who will be wealthier than people today and aspire to the kinds of food options currently found only in high income countries. This food must be produced ethically, considering both climate change and other environmental problems.[1] Additionally, food has a greater impact on human health than any other factors; therefore, promoting healthy diets is crucial for everyone's well-being as well as for containing the cost of medical treatment. It is widely accepted that if the food system continues its current path we will not be able to accomplish these goals. The food system needs to change fundamentally to meet these challenges, and Fourth Industrial Revolution-enabled technologies, among others, will be a key component of this transformation.[1,2]

The World Economic Forum's 2018 Innovation with a Purpose report found that healthcare has received cumulative start-up investments since 2010 that are ten times greater than those in the food industry, demonstrating that recent technological advancements have not been fully adopted by the food industry. In order to meet the dietary needs and food demands of a predicted population of 10 billion people by the middle of the century, alternative proteins that can replace conventional animal-based food are attracting significant financial investment, research focus, and media interest, though this does seem to be changing.[3,4] Although it is unknown how this market will develop, a significant disruption could happen shortly. The Fourth Industrial Revolution has made many of these potentially disruptive alternatives possible, which have enormous promise for everything from reducing greenhouse gas emissions to revolutionizing nutrition and health.[5,6]

Using meat substitutes instead of traditional meat may reduce adverse environmental impacts and improve public health. The two types of meat alternatives that we discuss are cultured meat (CM) and plant-based meat analogues (PBMAs). Despite their benefits, some people might not like some foods. Despite being typical cuts, neither PBMAs nor CM resemble a solid piece of meat (like a steak). Given that PBMAs and CM are novel foods, some people might avoid them or decide not to try them.[7,8] People may feel intimidated by PBMAs and CM because they have strong attachments to conventional meat or because it contradicts their social beliefs of being a meat eater. The material that is now available indicates that there is a considerable study

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gap because several meat substitutes are still mainly unknown or inaccessible.[9,10] To understand how customers view meat alternatives, it will be required to engage them in more direct interaction with the items. PBMA formulations are complex and usually incorporate genetically modified ingredients along with multiple other ingredients and with versatile processing methods. At a comparable price point, they are intended to mimic the nutritive value and organoleptic qualities of animal meat. Development is hampered by antinutrients, offensive tastes, sensory characteristics, unique allergies, nutrient bioavailability, and the need to identify necessary microbiological and chemical testing.[10−12] It is necessary to examine the long-term effects of a PBMA-based diet. PBMAs have the potential to revolutionize traditional protein sources by providing products that are more affordable and animal and environmentally friendly.[12−14]

Consumer demand for healthy diets, concern about rising meat prices, increased vegetarianism popularity, and growing consumer interest in related eating patterns such as the avoidance or reduction of red meat consumption have resulted in a steady increase in demand for the meat analogues and the use of an alternative source such as plant protein as ingredients in the human diet.[15,16]

Meat has a special place in the human diet. Modern humans have an innate preference for meat because it is both energy-dense and protein-rich, as we evolved from an environment where both energy and protein were scarce. In many societies, the consumption and provision of specific types of meat serves as a status symbol or a sign of hospitality and is considered important for social and nutritional purposes.[16−18] Furthermore, various societies have a long history of meat abstinence as well as intricate taboos that prevent people from eating certain types of meat that are likely rooted in the prevention of food poisoning.[19] As we have seen with numerous public health campaigns, aimed at encouraging healthier eating habits, these powerful cultural and biological drivers have had a significant impact on efforts to change diets. Because animal protein is a scarce resource in many developing countries, developing plant-based meat alternatives could help meet the population's protein needs and prevent protein-energy malnutrition.[20,21]

The environmental impact of meat production, particularly its greenhouse gas emissions, is a hot topic in the current environment. The effects vary greatly depending on the type of livestock and the method of production. The production of red meat (cow, sheep, and goat) is a significant source of greenhouse gases due to the methane produced during ruminant digestion.[22,23] Livestock production accounts for 15% of anthropogenic greenhouse gas emissions, with beef and dairy farming accounting for 40% (dairy production accounts for about 3%). Furthermore, livestock rearing can be a source of both point and dispersed pollution (including that caused by nitrogen, phosphorus, and pathogenic microorganisms), particularly in areas where manure and slurry management regulations are lax or nonexistent.[24]

When discussing meat substitutes and the need to reduce global meat consumption, it is critical to avoid policies that harm the health or livelihoods of some of the world's poorest and most vulnerable groups who rely on meat and livestock. Similarly, there is the possibility of people's livelihood being disrupted in middle- and high-income countries, particularly those with no other options for employment, and these transition costs will have to be carefully considered and planned for, as seen in the transition away from fossil-fuel-based jobs.[25,26] To summarize, if the social costs of adopting alternative proteins are perceived to be too high, public support for them is likely to be suppressed.[27−29]

Consumer demand for healthy diets, concern about rising meat prices, increased vegetarian popularity, and growing consumer interest in related eating patterns such as the avoidance or reduction of red meat consumption have resulted in a steady increase in demand for meat analogues and the use of an alternative source such as plant protein as ingredients in the human diet.[29−31] Many developing nations view animal protein as a scarce resource, so creating plant-based meat substitutes is one way to meet the population's protein needs and prevent protein-energy malnutrition.[32,33]

However, technological innovation in plant-based alternatives is not limited to genetic engineering, a contentious topic for numerous customers that can result in significant legal and regulatory barriers. Even in the absence of genetic engineering, there is enormous room for innovation in ingredient development. The overwhelming majority of plant-based meat products relies on a small number of plant proteins, with soy, pea, and wheat proteins accounting for the majority of the products.[33,34] Beyond these three crops, the vast array of available plant proteins remains largely unexplored. Recent studies have mentioned the usage of soy-based textured or texturized vegetable protein (TVP) and textured isolate soy protein (T-ISP) as a meat substitute with numerous economic and functional benefits. Soy-based TVPs are cholesterol-free plant-based protein products with low saturated fat and a high concentration of essential amino acids. TVP is manufactured through a high-pressure extrusion process followed by a final spinning or extraction of the finished product, which can then be used in meat analogues.[34]

The binding ability of the various ingredients in plant-based meat is critical, as nonadhesive behavior of varying plant ingredients can have a significant impact on the final analogy. Previously, egg solids, hydrocolloids, starch, and milk protein were used as binding agents in a variety of commercial products. Methylcellulose (MC) was used as a binder in this study. Binding abilities and moisture retention, boil-out control, increased volume, and texture improvement are all quality characteristics of MC in various types of meat analogues and processed meat.[34] The naturally occurring polymer, i.e., cellulose is converted to hypromellose (HPMC) or MC by means of synthetic modification and is considered safe for human consumption.

Furthermore, the FDA classifies MC as generally recognized as safe (GRAS) (21 CFR 182.1480) and allows it in USDA-regulated meat patties at concentrations up to 0.15% (9 CFR 3 t 8.7).[35] The use of binding agents in meat analogues has previously been extensively researched, but no attempt has been made to study the effects of MC on quality characteristics of PBMA patties. As a result, the purpose of this study was to assess the effects of MC on the quality characteristics of PBMAs with the incorporation of various texturized soy vegetable proteins.[35]

This review is a compilation of plant-based proteins for the formulation of meat analogues to ensure food safety and reduce pollution. Most of the plant proteins have been mentioned and studied in the literature; more in-depth knowledge about the selected materials is required.[35,36] This review is designed keeping the future benefits of researchers, academicians, and food safety in mind. Aside from that, consumer acceptability and processing advancement have been thoroughly discussed for their safe use in the formulation of meat analogues.[34−36] Future,

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research opportunities include developing better techniques for consumer education, providing more proof of the PBMA's health benefits, finding better protein sources to improve the quality of finished products, improving flavor and appearance, further examining and ensuring chemical safety, examining the mechanism of structure-based extraction or shearing processes, and developing techniques and standards, which have been briefly discussed.

2. HISTORY OF PLANT-BASED MEAT ALTERNATIVES

The market for meat alternatives made from plants is expanding. As part of the European Like Meat project, which investigated why consumers changed their diets to include meat substitutes, a meat replacement product was developed that imitates the fibrous structure, bite, and juicy mouth-feel of meat.[34,35] High-moisture extrusion during cooking plant proteins is changed during the procedure into a basic product with a structure resembling meat. Several protein sources were blended with different food items and tested to create this foundational product. Spices and smell compounds, in addition to flavor components, were created. Additionally, the microbiome received attention. In addition to their potential for expansion in the finished, packaged food product and their rates of inactivation throughout the cooking and extrusion processes, the microbiota was investigated in raw materials.[36,37]

Meat analogues, often referred to as meat substitutes, meat surrogates, and meat replacement foods, initially appeared in Western markets in the early 1960s. In contrast, tofu and tempeh have been eaten in Asia for centuries. Along with the development of these traditional Asian products, the introduction of meat alternatives began with the development of dry TVP, which is produced by heating extrusion of defatted soy meal, soy protein concentrate, or wheat gluten.[38] Because they are elastic and slightly spongy, these products work well in burgers, stews, and sauces. Shredded TVP and mycoprotein are two examples of fibrous raw materials that can be used to mimic the elastic and fibrous characteristics of meat.[39,40] These fundamental elements are generated, together with water, a binder, and other additives, and then steam-baked. In contrast to TVP, these items offer distinct shape and flavor variations as well as goods that meet standards like "vegan", "organic", and "gluten-free", and they can be created from a range of materials. The development of the high-moisture cooking extrusion technique in the 1990s created new possibilities for texturizing dietary proteins into distinctive fibrous structures that resembled muscular flesh. This process produces a fibrous, meat-like structure that has the same bite and feeling as meat in a single step and has a similar moisture content.[41−43] We now have more knowledge about prospective raw materials and their characteristics, impacts, and interactions of additional functional additives and flavoring, thanks to the Like Meat effort.[43,44] A new generation of meat substitutes was able to be introduced to the market because of innovative smart packaging and preservation solutions and product development that was consumer-focused, updated, and with improved postextrusion operations.[44,45]

A second generation of PBMAs designed for carnivores was created recently, while the first generation of PBMAs emerged in the 1960s. The origins of history can be found in prehistoric Asian cultures. Two commonly studied structuring methods are extrusion and shear cell operations; however, to produce PBMAs, it is also essential to optimize the overall flavor and appearance, control biological and chemical safety, and select the proper protein sources.[46−49] Although still insufficient, the PBMA is becoming more well-liked by customers.

In countries like China and India, processed plant-based protein products have been consumed since the beginning of civilization. Tempeh and Seitan are two examples of plant-based protein foods that have been popular in these countries for a very long time.[50] In vegetarian and Buddhist cuisine, these traditional plant-based dishes were widely utilized as a protein alternative. More and more people are becoming vegetarians, especially in industrialized countries, which has led to the development of more products made from plants.[51] The concept of PBMAs was further expanded when TVP was created in the 1960s and utilized as the primary ingredient in vegan versions of meat-based dishes like burgers and bacon. In order to satisfy meat eaters, businesses like Impossible Foods and Beyond Meat have developed a new generation of PBMAs. The most recent PBMA products have comparable structures and smells and even a bleeding appearance similar to animal meat, which has proven to be popular with consumers.[52,53]

2.1. The Beginnings. Seitan, tofu, and other conventional foods have been used as meat replacements for centuries. Tofu, a popular meat replacement, was developed in China during the Han era (206 BC−220 AD). Tofu was widely consumed throughout the Tang dynasty (618−907) and is said to have arrived in Japan during the late Tang or early Song period.[54]

2.2. The Initial 20th Period. Pioneers like John Harvey Kellogg created nut- and cereal-based goods like Nuttose and Protose in the early 20th century to advance health. Along with traditional Asian foods, dry texturized vegetable protein (made from extruded, defatted soy flour and soy protein concentrates) was also created.[54]

2.3. The Mid to Late 20th Century. Plant protein concentrates, isolates, and textured proteins significantly improved after the Second World War as a result of apparent developments in the production and packaging sectors.[55,56] These developments came at a time when the consumption of meat was expanding in many industrialized nations as a result of expanded farmland and improved animal husbandry. In the US, Tofurky-like goods that catered to a niche vegetarian market initially surfaced in 1980.[57]

2.4. The Early 21st Century. Burger King introduced the first meat substitute in America in 2002 as a traditional plant-based burger. A rise in consumer knowledge of the environmental and health effects of their meals coincided with the growth in demand for meat alternatives in the new millennium.[58]

Because of products like the Impossible Burger and the Byeon Burger, the market for plant-based meat has grown by 50%.[58] The goal of plant-based meat is to replicate the taste, texture, appearance, and functionality of classic sausages, burgers, and fillets. Modern improvements in food science and production helped achieve these goals. Additionally, plant-based proteins, lipids, gums, spices, extruders, and other novel processing techniques have been combined to make meat replacements that have great consumer demand.[58,59]

3. IMPACT OF TRADITIONAL MEAT PRODUCTION

3.1. Environment. The efficiency, or comparison of the food produced using natural resources, varies with different food systems. All food production requires valuable resources like land, water, and energy.[59] More than 70% of the energy used in traditional meat production is either lost through excretion or consumed during animal body growth and development, making

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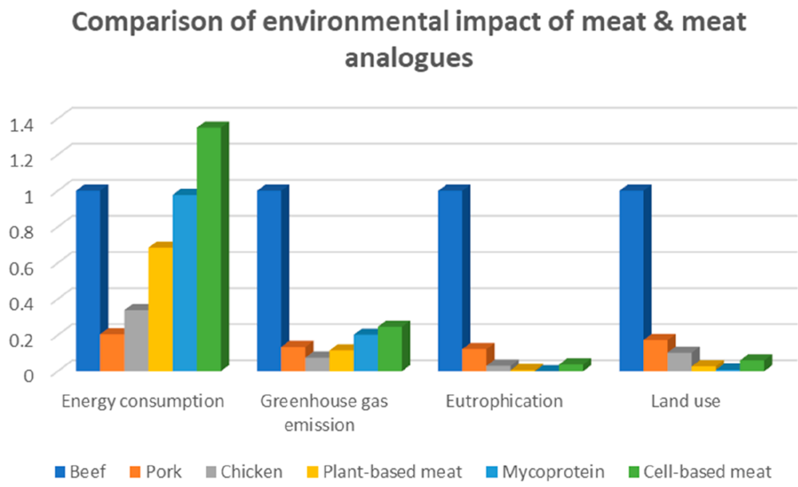

Figure 1. Comparison of the environmental impact of meat and meat analogues.

it an inherently inefficient process. Researchers concluded that the production of meat protein foods required more land, water, fossil fuels, and phosphate rock than foods based on soybeans. They did this by using data from published life cycle assessment (LCA) studies and other sources.[59,60] In 555 LCA analyses, the greenhouse gas (GHG) emissions from agricultural and animal products were expressed as CO_2 equivalents (CO_2−Ceq). It was discovered that foods made from plants emit fewer greenhouse gases than foods made from animals. The study found that the production of legumes generates about 250 times fewer emissions than the production of ruminant meat, such as beef and lamb.[60,61]

There are three major environmental issues associated with meat production:

- Feed sourcing
- Manure processing
- Climate change

To raise meat, a lot of feed is required. Large monoculture crop fields for livestock feeding have been created on millions of acres by ploughing. For instance, the energy needs of various livestock, such as ruminant and nonruminant creatures, and the same types of livestock living in various systems, such as free range versus caged environments, vary. Even with technological improvements, the processes used to produce meat are still much less energy efficient than those used to grow and harvest plants. For instance, a substantial quantity of crops, such as grains and fossil fuels, are needed to power and feed farm infrastructures and animals.[61]

Changes in diet are an effective way to reduce GHG emissions as well as land use demand, according to a systematic review. For instance, a vegan diet can reduce greenhouse gas emissions by 25% to 55% and land use demand by 50% to 60%, while eating some plant-based foods in place of meat can reduce emissions by 5% and land use demand by 15%.[61,62]

Below, four types of meat substitutes were compared, including vegetarian, vegan, insect-based, and fortification-free meat substitutes. The results showed that vegan substitutes can reduce up to 87% of indicators such as climate change, land use, and fossil fuel depletion.[62]

Data are normalized to the impact of beef production. Eutrophication does not include data for mycoproteins. Land, emissions, and energy data for mycoprotein were adapted from 2015 LCA. Data for beef, pork, chicken, and CBM were adapted from a 2015 life-cycle assessment. Data for PBM were adapted from an Impossible Beef LCA and a Beyond Meat life-cycle assessment (energy use)[63−65] (Figure 1).

3.2. Health. Traditionally, meat has provided people with the nutrients and energy they require to get through the day. Despite this, the World Health Organization's International Agency for Research on Cancer (IARC) has determined that red meat, such as beef, is a likely cause of cancer in humans (Group 2A), whereas processed meat is carcinogenic (Group 1). These distinctions are based on evidence linking certain types of meat to colorectal cancer. Unfortunately, most of the meat available today is processed, including sausages, smoked meat, ham, and bacon, even though beef and pork, the world's two most popular meats, are both classified as red meat.[64,65]

The scientific community and the general public are concerned about the health consequences of meat consumption. Epidemiological studies and meta-analyses are two techniques commonly used to estimate the health effects of meat consumption. Controlled animal models and cell-line-based experiments have also been used to learn more about how meat affects the body.[65] Despite the lack of direct evidence, the studies reviewed showed that high consumption of processed and red meat is associated with higher mortality rates.

3.3. Emergence of Toxicants. Toxins released during the manufacturing process, as well as the presence of high levels of saturated fatty acids in processed and red meat, may be responsible for their (likely) carcinogenic properties. Polycyclic aromatic hydrocarbons and heterocyclic aromatic amines, two well-known mutagenic substances, are common process-induced toxicants in meat products.[65,66] Furthermore, it has been amply demonstrated that people who consume a lot of saturated fat are more likely to develop chronic illnesses because their bodies have high levels of low-density lipoproteins. Heme iron, which has been linked to stomach and esophageal cancers, and high levels of salt, which can cause blood pressure spikes, are two other potentially harmful components of processed meat and (or) red meat.[66]

3.4. Animal Welfare Concerns. Animal welfare issues are frequently caused by poor farm management practices. On farms, for example, livestock may be kicked, thrown, or beaten. Furthermore, farmers frequently demonstrate a shocking lack of concern for health issues that can arise as a result of breeding. Advanced ocular neoplasia in cattle, for example, is frequently

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overlooked, whereas necrotic rectal prolapse in pigs can be fatal. Factory farming, which raises livestock at extremely high densities, is another significant contributor to animal welfare issues.[66]

For example, invasive practices such as castration deprive livestock of their natural behaviors, causing them to exhibit abnormal behaviors such as cannibalism. Alternative farming practices, such as free range, can help to resolve these issues, but new issues have emerged continuously.[67]

There are serious concerns about how animals are treated during the transport and slaughter processes. There is a high mortality rate and frequent injuries when animals are transported to slaughter houses. For example, using excessive force to drive animals off the trucks can result in additional injuries. Although more efficient transportation methods and skilled drivers can reduce animal cruelty, all issues cannot be completely resolved. The main issues with animal treatment, however, arise during the slaughtering process.[67,68] According to the animal welfare standard, livestock should be slaughtered in as little pain and distress as possible. Standard operating procedures such as preslaughter stunning and auditing programmes have been established to maintain dependable animal welfare standards in slaughter houses.[68]

As a result of their growing awareness of livestock treatment and lifestyle, many consumers have developed serious concerns for the general welfare of the animals. This concern, along with the environmental and health benefits, has played an important role in the shift toward vegetarianism and veganism in many Western societies.[68−77]

4. FRAMING THE FUTURE OF MEAT: INNOVATION AND ALTERNATIVE PROTEINS

People choose which foods to eat based on price and their deeply held beliefs about what is good or bad about them. These beliefs are influenced in part by the interplay of a complex collection of stories, specifically the food-related stories we tell one another. Understanding the dynamic interactions of the various stakeholders attempting to shape these narratives is critical for anticipating how diets will change and promoting more sustainable and healthy food options.[77]

Alternative proteins, changes to current production systems, and changing consumer preferences are three potential pathways for meeting the world's growing population's protein needs in a sustainable and healthy manner, according to the future initiative. The first pathway, which is the focus of this report, is the development of alternative protein products. There has recently been a surge of innovation in this area, with new purely plant-based alternatives, products based on insects and other novel protein sources, and the use of cutting-edge biotechnology to develop cultured meat.[77,78]

Products in this category have grown in popularity over the past decade as a result of new technological advancements aimed at replicating specific meat characteristics down to the molecular level. Several products are designed to be "viscerally equivalent" to farmed meats in order to attract meat lovers. Most of these plant-based alternatives use soy, wheat, or pea protein isolates or concentrates as their primary protein source, though fungi (such as mycoprotein) and lupin beans are also available.[78] Popular plant-based substitute brands and products include Gardein Meatless Meatballs, Morningstar Farms Original Chic Patties, Beyond Meat's Beyond Burger, and Impossible Foods' Impossible Burger (World economic forum report (2019)).

4.1. Growing Popularity of Meat Alternatives in Future Perspectives.

Consumers who are worried about their health are increasingly finding their needs and wants met in the global food market. Plant-based meat (analogues, substitutes, or alternatives) is gaining popularity as an alternative source of protein, and several innovations and solutions have been proposed.[78,79]

Consumers' eating preferences have changed significantly, with more people favoring sustainably produced plant-based goods. Aside from that, there are customers who care about the environment and are keen to find different ways to reduce the carbon imprint that is frequently created during the production of conventional beef, intake of meat, and products made from meat.[79] It is common knowledge that raising animals for food is not an environmentally friendly process. The possibility of contracting an animal-borne illness from eating meat has gradually imprinted a negative effect on consumers. On the other hand, there are less chances of contamination and deterioration during the preparation of plant-based foods.[79,80]

Food industries are currently making large investments as a result of their foresight into the importance of meat alternatives. Alternative meat products are primarily plant based and include a variety of processed soy products (tofu, soya fish), cereal-based goods (wheat gluten: seitan, rice-based products), and legume-based products. Depending on the country, this category represents between 10% and 69% of customers. The value of the total AP market is expected to reach $290 billion by 2035. In 2020, the market for plant-based foods alone was estimated to be worth $29.4 billion.[80]

According to Graça et al.,[81] different consumer mindsets toward meat include those who are attached to it, show disdain for it, or have a low level of attachment. In fact, consumer attitudes about increasing or reducing meat consumption often take an "all-or-nothing" stance. As a result of this binary perspective, nonvegetarian customers regard vegetables as a complement rather than a meat substitute. Additionally, they frequently link AP intake to adopting a vegetarian or vegan lifestyle.[81] Further, meat eaters frequently reject diets that limit their intake of meat,[80,81] and they also frequently dismiss arguments for doing so. But if customers are persuaded to alter their meat-eating habits in order to lessen guilt or affective connections that emphasize meat's detrimental effects, this attachment may be broken. There is a growing consensus that major health and sustainability challenges in the food systems need a shift from meat-based diets toward more plant-based ones. The research still lacks the theoretical and empirical rigor necessary to support this move, though. It is more challenging to organize and carry out coordinated measures among stakeholders and decision-makers to address these important concerns as a result of this fragmentation.[81,82]

The current evaluation addresses this constraint and has the following two objectives:

- To map the elements (i.e., actual or potential barriers and enablers) related to consuming less meat, replacing it with plants, and adopting a plant-based diet.
- Creating an organized, comprehensive theoretical framework for behavior modification that incorporates the body of available research (COM-B system). The results of this review will be of interest to a wide range of audiences and professions interested in promoting sustainable living and health gains through food choices. A small number of psychological and physical enablers and obstacles were

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identified in the investigation, which may be significant for reducing meat intake and increasing plant-based diets.[82–84]

Regarding psychological capacity, one study with consumers who consumed a plant-based diet highlighted the process of acquiring new knowledge and developing capacity (such as learning how to prepare new meals) as essential (but difficult) to their successful transition.[82,83]

Another survey revealed that health food shops, the Internet, books, periodicals, and newspapers were the most popular information sources.[83] However, one study with former meat avoiders found that the challenge of preparing new meals while on a plant-based diet was a significant obstacle.[84] The lack of knowledge and poor cooking abilities have also been noted as obstacles toward adopting a plant-based diet in research with consumers who regularly consume meat or meat-based products.[84,85] Regarding physical limitations, a study found that being more sensitive to bitter flavors was linked to less favorable opinions toward plant-based diets and favorable attitudes toward dishes high in animal products.[85]

4.2. Creating a Meat-Like Structure and Maintaining Food Quality and Safety. Due to the world population's rapid growth and its effects on the consumption of natural resources, we are observing an increasing shortage of proteins with high biological value. Concerns about the health of both humans and animals have also fueled the creation of plant-based meat replacements. The industry for plant-based meat replacements is expanding swiftly in response to rising consumer demand. Soy protein has been effectively exploited in the development of meat substitutes and has become the most well-known vegetarian protein source due to its exceptional gelation properties and ability to create fibrous structures.[85,86]

Future research should concentrate on developing not only the innovative but also the cost-effective technologies concerning the development of plant-based meat analogues. More studies must focus on enhancing product taste and improving product nutrition and safety in order to meet consumer needs for high-quality products.[86]

How to feed a growing population without using an excessive amount of natural resources or irreparably harming the environment is the critical challenge the world is confronting. Important ecological processes including carbon sequestration, nitrogen cycling, and agricultural landscape preservation can be supported by sustainable management of animal production to overcome the above-mentioned obstacles. However, in the current climate, there is a cause of concern regarding the effects of the livestock sector on the climate and environment, animal welfare, and potential threats to human health (including the use of water and land resources, greenhouse gas emissions, and energy consumption, etc.).[86,87] There will likely be 9 billion people on the earth by the year 2050, which will call for growth in the meat industry. As a result, the development of meat alternatives based on vegetable protein helps to address the problems while providing vegetarians with a new food choice.

Soy protein has been identified as a possible candidate to be used in the production of meat substitutes manufactured from vegetable proteins due to its excellent gelation properties, superior nutritional content, and inexpensive cost. Tofu is a traditional soy-protein-based meat substitute that has a long history and is still popular.[87,88] One of the key elements for consumer acceptability of meat substitutes made of vegetable proteins is their fibrous anisotropic structure, which contributes to creating sensory and textural qualities that are like those of real meat. One of the most popular and extensively researched methods for creating this meat-like fiber structure from plant proteins now is extrusion technology. Soy protein, the primary raw material, goes through several physical and chemical changes while being subjected to thermomechanical treatment throughout the extrusion process, eventually forming an anisotropic structure resembling flesh.[88] The interaction between raw materials, the creation of the fiber structure, and the quality of the finished product are all greatly influenced by the extrusion temperature, screw speed, feed rate, and material moisture content for high moisture extrusion. In order to successfully formulate a soy protein meat substitute, wheat gluten (WG) should also be included as a binder to maintain the fiber structure. Additionally, pea proteins and other plant proteins have both demonstrated the potential to be used to create meat substitutes.[88]

4.2.1. Development of Structure. Animal- and plant-derived proteins must unfold, cross-link, and align in order to form microscopic and macroscopic fibers. The process conditions are provided by the high moisture cooking extrusion method, which has a water content of up to 70%. Using corotating twin screw extruders equipped with long screws and specially designed long cooling dies, the low viscosity bulk is effectively converted into a protein strand with a distinctive fibrous structure. First, components are continually added to a long extruder barrel, most notably water and food protein powders. As the material is carried toward the die area and steadily heated to temperatures between 130 and 180 °C, corotating screws thoroughly integrate the contents. There are several effects of the rapid cooling of the extended die portion. In order to limit product expansion caused by the evaporation of superheated water, the mass is cooled to a core temperature below 100 °C.[88,89] Additionally, the temperature difference between the core of the strand and the die wall improves shear flow. Cooling, noncovalent hydrogen bonding, van der Waals interactions, and electrostatic interactions all happen simultaneously. As the viscosity rises, the bulk transforms into a thread with a meat-like consistency. The production of meat analogues in these cooking extruders involves a wide range of machinery and industrial processes.[89]

The composition, diversity, and water content of the matrix have a significant impact on the final output. Regarding the specific impacts of each parameter and their interactions on the production of fiber and the quality of the completed product, only soy, wheat, and pea proteins are discussed in the literature. It has been proven that using proteins with enough cross-linking ability in the recipe is advantageous.[89,90] Therefore, the Like Meat initiative aims to increase this understanding to encompass intricate recipes and the effects of various ingredients on the growth of fiber.

In order to prepare goods with a meat-like bite and a juicy mouthfeel and to avoid strong, unpleasant flavors from single ingredients, protein compounds were often combined with additional ingredients like starches and fibers.[90]

Additionally, this made it possible for recipes to be modularly modified for special requirements like vegetarian, vegan, and gluten-free. The created strand is used as a raw material in several postextrusion processing processes to produce vegetarian cuisine. The tools that are typically used for preparing meat can often be employed. Like Meat is precooked, making preparation easy and, depending on the product, comparable to that of the suitable meat product.[90,91]

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4.2.2. Flavor and Taste. A major prerequisite for consumer acceptance and the introduction of new meat alternatives to the market, in addition to textural attributes, is an appealing flavor. There must be no off flavors in these products, and the flavor must meet consumer expectations. Many meat replacements developed in the past, however, lacked flavor and aroma, which may have contributed to their failure on the market.[91]

Two methods of flavoring food exist:

- Adding flavors or spices.
- Using compounds that are odorless and tasteless but are thermally processed into chemicals that have sensory properties.

One typical and well-known procedure is the Maillard reaction. This reaction, which involves heating almost all foods, bioconverts amino acids and sugars into a range of flavors and colors. In order to produce meat alternatives with excellent flavor and aroma quality, the Like Meat project applied and investigated every possible flavoring application. The pure Like Meat products were not impacted by an off-flavor because the protein raw components were carefully chosen and blended. The meat substitutes did not even have much of a scent.

The product felt like beef and had a flavor that was almost dull.[90,91] Depending on the chemical admixtures, some of the strands even had a slight scent of chicken meat. A different technique of flavoring was found by adding flavor precursors, such as amino acids and sugars; however, there were some limitations on the precursors' combinations and dosages.

4.2.3. Microbial Safety. Because of their high levels of protein and moisture as well as almost neutral pH, meat mimics are prone to rotting. Microbial activity is the primary factor, with microbial enzymes and metabolites acting as supporting players. In the academic literature, there are limited reports of the microflora of high-moisture meat substitutes consisting of plant proteins. In order to find and describe any important spoiling or potentially harmful bacteria, a complete microbiological analysis of the raw materials and the newly generated products was necessary. Due to its low water activity, plant-based protein powder does not promote the growth of bacteria. Endospore-forming microbes, like Bacillus and Clostridium species, could, nevertheless, survive the extrusion process.[91] Depending on the microbial load of the chosen raw materials, relevant microbe concentrations may show up in the premixtures and recipes. This covers the potential for hazardous and poisonous microbial species to exist. Based on the process temperature and pressure parameters (130−180 °C, 20−50 bar for seconds to minutes), as well as the water content, vegetative microbial cells and bacterial endospores are inactivated to a very high level during a typical cooking extrusion process. Each postprocessing step is crucial for product cleanliness, and handling and shipping the meat substitute must be done as carefully as possible to reduce the risk of recontamination.[90,91]

4.3. Consumer Acceptability of Plant-Based Meat Alternatives. A search for alternative sustainable food sources has been sparked by the mounting strain on animal agriculture as a result of the negative effects meat consumption has on human health, the environment, and animal welfare. As a result, alternatives to traditional animal protein sources, such as plant-based, fungal-based, and hybrid meats, have been created. Traditional meat eaters frequently view hybrid meat as a more alluring substitute. Figure 2 and Table 1 summarize various sources of plant proteins that can be used for framing the meat analogues and give a brief comparison of meat analogues.

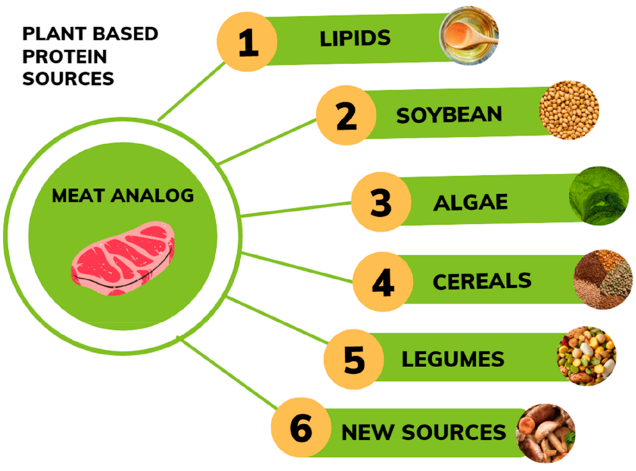

Figure 2. Plant-based protein sources used in novel human foods.

Recent research has shown that plant-based meat substitutes will not satisfy meat eaters since they have lesser expectations for flavor. They thought the plant-based substitutes were healthier. Despite being equally or more nutritious than ordinary meat products, cultured meat products were perceived unfavorably by meat eaters. These findings imply that there is a chance to encourage (motivate) the acceptance of meat replacements based on their perceived healthfulness, which would at least somewhat offset the decreased expected taste pleasantness and other drawbacks (i.e., barriers). The primary target consumers for conventional and first-generation PBMA products were vegetarians and infrequent meat eaters who did not expect the same textures and flavors from plant-based protein substitutes.[90,93] However, the most current PBMA products attempt to be practically indistinguishable from conventional meat products in order to attract consumers with mild to heavy meat diets. It is difficult to convince people to favor PBMAs over traditional meat, given that consumer behavior is influenced by a variety of factors. The food sector can endeavor to enhance the characteristics of plant-based replacements, such as their structural and sensory similarity to meat, in order to raise consumer acceptability of PBMAs.[91,92]

Numerous published articles have employed consumer surveys to analyze major contributing elements and customer perceptions of PBMAs. These studies suggest that most consumer acceptance of PBMAs is still low and that the factors influencing consumers' perceptions of PBMAs can be divided into two categories: personal aspects, such as unique culinary preferences and the reasons why people choose foods, and product-specific aspects, such as PBMA's sensory effect, in line with an illustrative study on the selection of consumer products.

4.3.1. Techniques to Raise the Acceptability of Meat Replacements. Although PBMAs are not typically recognized by customers, over the past few years, this has been shifting. As a result, these summaries show that the most crucial measure to take into account to address a crucial issue for PBMA development is to increase consumer approval. This can be done by raising the standards of these products overall and raising consumer knowledge of PBMAs.[92,93]

- A rational strategy should be developed to help educate customers and provide a guide for bringing attention to PBMAs' advantageous impacts on human health and the environment. With greater awareness, the market for PBMA products will surely grow.

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Table 1. Comparative Study of Meat Analogues

Meat analogues	Position as meat alternative	Application	References
Cereal-based (Wheat)	It is used as a potent meat alternative due to the structural buildup property of gluten protein.	Seitan (vegetarian sausages and nuggets)	89
Rice-based	It is utilized in combination with soy protein to complement the deficiencies.	Tofu	91
Legume-based	It is regarded as poor man's meat, and pea protein among the legumes is highly utilized.	Meat analogues from pea protein isolates	90
Soy protein	It has a considerable amount of protein and provides efficient texture and quality attributes to meat analogues.	Textured vegetable protein	92
Microbial origin	Protein sources derived from microorganisms (bacteria, yeast, microalgae).	Single cell proteins, mycoproteins	89

- By including foods that support excellent health, the health and nutritional image of the product can be improved in order to convince consumers of the advantages of PBMAs.[93]
- By using different protein combinations (combinations of amino acids), flavoring agents, and other additives that improve the flavor and palatability of the protein sources while also enhancing their textural and structural properties.
- The need to continue research areas like the mechanism of structure development during the extrusion and shear processes, as well as the standards and methods for judging quality, cannot be overstated.[93,94] The former serves as the cornerstone for PBMA product structure improvements to come, and the latter serves as the cornerstone for PBMA production quality assurance.
- It is necessary to conduct more research on the safety aspects of PBMAs, especially with relation to chemical safety. For instance, the foodomics approach, particularly mass-spectrum-based techniques, can be utilized to detect the presence of external pollutants and/or process-induced toxicants in PBMAs.[94]

5. MEAT ANALOGUES

5.1. Soy Meat/Textured Vegetable Protein. Soy meat or TVP is procured from soybeans mostly in Asian countries. Even though soy meat has over 50% protein, its protein level decreases when texture vegetable protein is rehydrated.[93,94] Vegetable protein with this texture was first created in the USA and introduced to the European market in the late 1960s.

TVP can be defined as "texturates", "soy meat", or "textured soy protein" made from plant-based protein sources and water by transforming a powder-type material to a structured material. While the most common low-moisture texturization approach is extrusion, the most common high-moisture texturization approaches are extrusion and shear cell technology that enable the formation of anisotropic fibrous structures of single or blends of plant proteins.[93] Through adjusting equipment and the structuring process parameters, textures, flavors, and shapes of TVP can be modulated to fit various vegan or hybrid products.

The quality of TVP has improved drastically in the last 40 years. The textured vegetable protein is fabricated using hot extrusion of defatted soy proteins, resulting in expanded high protein chunks, nuggets, strips, grains, and other shapes. Vegetable protein has seen drastic improvement in texture and quality during the past 40 years. The denatured proteins give these vegetable proteins a texture like meat. Vegetable protein with a fibrous, insoluble, porous structure can absorb liquids like water. TVP can be used as a meat extender in meat analogues or consumed directly. The dependency on raw materials for extruder texturization distinguishes meat extenders from meat analogues. Meat extenders are not comparable to meat in look, texture, or feeling when cooked alone. These textured goods are combined with meat for additional processing to enhance their general functional qualities. However, when hydrated and cooked, meat analogues resemble meat a lot in terms of look, color, flavor, and texture.[92−94]

The primary use of TVP is the creation of meat substitutes including sausages, patties, and nuggets.[93,94] To increase meat's viscoelasticity, color stability, moisture retention, firmness, and juiciness, LM-TVP is employed as a meat extender. The most widely used TVP is produced with soy, wheat, or pea proteins or combinations of those three. Both a porous structure and a steady shelf life define LM-TVP. When hydrated, the texture changes from hard and gritty to chewy and juicy to resemble flesh. There is growing interest in enhancing the structuring ability of protein sources to produce bites that resemble flesh. Furthermore, food designers are experimenting with various protein blends to make TVP with a variety of textures, flavors, and nutritional benefits as well as to provide a vast portfolio that seeks versatility and high quality (meat-like sensation).[91−93]

5.2. Wheat Gluten/Seitan. Cereals are a crucial food crop, and the goods made from grain are crucial to the food processing sector. Some of the major uses for cereal proteins include seeds, flour, and flakes. Typically, wheat protein is made from gluten that has been processed and extruded to resemble meat in texture.[93,94] Wheat gluten is a textured vegetable protein that is employed in food products that can be used as meat extenders and meat substitutes. Gluten can be utilized as a binding agent and extender in ground beef patties to produce altered goods. After being hydrated, gluten could be extruded, given texture, and transformed into fibers to create a variety of meat alternatives.[93]

Another vegetarian meat substitute called "wheat meat" or "wheat gluten" is seitan. Until the chewy mass, or proteinaceous gluten, is generated, wheat flour dough is continuously washed to produce seitan. Seitan is a chewy, delicious alternative to meat that is a great choice for people who are not gluten allergic. The main reason seitan-based meat replacements such as veggie burgers, sausages, and nuggets are regarded as the least expensive is that they are made from basic raw materials. Products made of seitan are simple to handle and can be seasoned and prepared in a variety of ways. The chewy fiber textures that generate the homogeneity of meat have a consistency that is quite like seitan.[92,93]

5.3. Rice-Based Products. Risofu is a brand of rice-based sausages and burgers made by the American business Bahama Rice Burger. The name "Risofu" is a combination of the Italian words "riso" (rice) and "tofu" (rice tofu). The Shan region of Thailand, where the tofu made from rice is produced, served as inspiration for the product's development by the company. White, brown, and wild rice are combined to make Risofu in order to maximize nutrient content. Further, rice protein has no

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beany flavor which gives it an added advantage in being used for various formulation developments without impacting the targeted flavor of food.[93,94]

5.4. Legume Protein. Only cereal grasses are more important than the 27% of primary crops produced worldwide that belong to the legume family of plants. The primary element of a diet based on beans is protein. Seed protein concentration ranges from 20% to 30% of the total dry weight in many more species. Pea protein was shown to be the source of legume proteins that formed gels, emulsified, and stabilized foams, which is a desirable functional quality required for the development of superior quality meat analogues. Other sources of legumes include chickpeas, lentils, lupines, and other types of beans.[94] In the past, scientists have successfully created meat analogues from pea protein isolates (90% protein), gluten (80% protein), and starch at high moisture, which have a fibrous texture like that of chicken and fish meat. Legume protein, which is regarded as a "poor man's meat" in some parts of the world, is crucial for human nutrition.

Due to economic factors, the amount of meat made from legumes has greatly increased, notably in terms of quality, texture, and other useful characteristics.[94,95]

5.5. Mycoprotein. From 2.6 to 7 billion people, the population of the world has expanded up to 250% over the past 60 years.[94] By 2042, if population growth continues at the current rate, there may be issues providing food for all 9 billion people.[24] According to estimates given by the World Health Organization (WHO), 12,000,000 people die each year from famine, malnutrition, and related diseases in underdeveloped nations.[95] Nearly a billion people worldwide cannot afford diets with adequate protein and calorie contents.[96] Serious medical conditions including weak muscles, stunted growth, and a compromised immune system are caused by inadequate protein sources. On the other hand, one of the most dangerous issues is the large intake of animal products by Westerners (86.7 kg of meat with bones per capita annually) and some emerging nations. Therefore, it is crucial for the food industry to introduce suitable substitutes for animal proteins, especially meats, that have lower overall costs and resource use.

Modified meats, made from genetically altered organisms (GMOs), cultured meats, made from in vitro cell or tissue cultures, and meat substitutes made from plants and single-cell proteins (SCPs) are some examples of artificial meats (Maga and Murray, 2010; Van Der Spiegel et al., 2013). A pure or mixed culture of bacteria, yeast, fungus, and microalgae is said to be the source of the SCP, a protein having microbial origin.[24] Fibrous fungus is one of the many origins of SCPs. Mycoproteins, such as those from *Fusarium* (*F.*) *venenatum*, which are being used in food products under the brand name Quorn, are produced proteins.[96]

"Generally Recognized as Safe" is how mycoproteins are classified (FDA, 2002). In 100 g of dry matter, mycoproteins typically contain 13 g of lipid, 45 g of protein, 10 g of carbohydrate, 25 g of fiber, and several vitamins and minerals.[97] The biological significance of the proteins in mycoproteins is like that of milk proteins, according to research done on human volunteers. Furthermore, toxicology research has demonstrated that mycoproteins have no detrimental impact on the health development of both people and animals. However, neither the long-term nor the short-term use of the mycoproteins raises any general health issues.[97] Mycoproteins have a nearly 1.0 protein digestibility corrected amino acid score (PDCAAS).

The fiber content of mycoproteins does not appear to have any negative effects on the absorption of minerals. However, there are case reports of people who are intolerant to mycoproteins, but their level of sensitivity is lower than that of soy and egg.[97,98] More studies have been done on the creation of SCP in the form of meat substitutes, as a result of growing concerns about the food crisis or a lack of wholesome foods and keeping population growth and environmental problems in consideration. Prior studies concentrated on different SCP production techniques using microbes and the best ways to increase mycoprotein yields and improve their nutritional properties. Still, very scarce information is available on various aspects of mycoprotein replacement of meat.

6. TECHNIQUES USED FOR PRODUCTION OF PBMAS

6.1. Extrusion Technique. This method involves continuous churning, shearing, and heating with viscous formulations in a hot barrel. It is a multivariate complex thermomechanical process. Formulations with the necessary viscosity are often made using one or twin-screw extruders. The heated barrel's cooked bulk is quickly cooled to harden the fiber or strand that has been extended out of the nozzle. To achieve a good textural pattern on a meat analogue, the viscosity of the extruded material is maintained at the proper temperature, moisture, and pressure.[98,99] Nowadays, the approach is primarily used because of its reliability and economical value. The feed formulation, cooling die design, and operating conditions of the extruder can all be used to regulate the distinct shape, texture, and functional property of the food chunk. Depending on how much water is used in the extrusion unit to produce an analogue of a slice of meat, the extrusion procedures can be classified as high-moisture processes or low-moisture processes. Figure 3 highlights the various parts of the screw extrusion and process of PBMAs.

Three steps can be used to condense the processes:

- Preconditioning of the material outside the extruder,
- Mixing/cooking inside the extruder barrel, and
- Cooling in the die.

The textured meat substitute is rehydrated before being cooked or fried in low-moisture extrusion. When the food item is dipped in cream, it behaves similarly to a sponge and quickly absorbs the water. In beef patties and sausages, it is best used as a meat extender.

The texturized chunks are thoroughly hydrated throughout the extrusion process in high-moisture extrusion, and the moisture content is then maintained by freezing. After preconditioning the raw material, the twin-screw rotator raises the processing temperature up to 130−180 °C as a result of the mechanical energy lost during operation. The protein eventually begins to melt in the extruder barrel, and the viscoelastic mass is then exposed to the protracted cooling die. This produces structurally matched texturized proteins, prevents the expansion of newly generated food material, and makes it simple to pack food in wet conditions into pouches, cans, or frozen food.[98]

6.2. Spinning Technique. A sophisticated method for creating fine fibers uses high-speed spinning to produce mimicked meat from concentrated plant protein. It is a delicate procedure that uses a lot of water and acid/alkaline solvents and produces a lot of trash. This process is comparable to how textile fibers are spun. In an affordable procedure called electrospin, a mixture of proteins and other polymers is created according to their solubility, viscosity, conductivity, and other properties.

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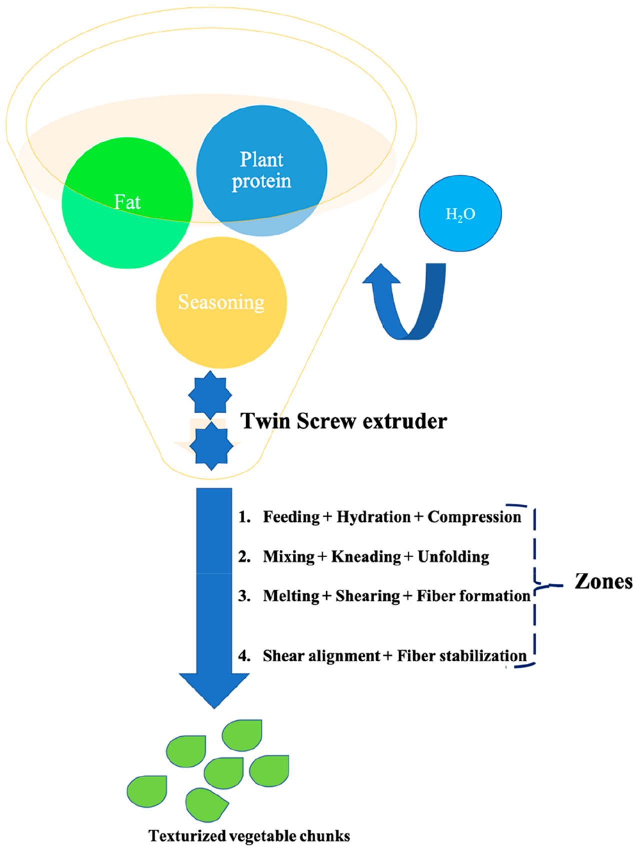

Figure 3. Extrusion technique of making texturized plant-based meat analogues.

If all conditions are satisfied, the polymeric solution forms a Taylor cone, electrically spins to create a fine thread or fibril, and finally dries to create entangled polymers that may be retrieved using the related nozzle. Several food-grade reagents (color, stabilizer, and aromatic chemicals) along with gluten (wheat protein) or zein (maize protein) in combination with polymers are suitable in this spin method for generating textured meat analogues. The benefits include low price, homogeneous fibril diameter, and scalable production. Controlling the various conditions necessary to electrospin plant proteins is challenging.[98]

6.3. Freeze Structuring Technique. The production of a fibrous meat analogue involves freezing a plant-based protein emulsion and allowing the ice crystals to form, which in turn creates an ordered and distinctive porosity, resulting in a desirable fibrous microstructure. Although it is made from a source of vegetable protein, the microfibrous structure, with its layers covering one another like a sheet, is like that of animal flesh muscles. Using this method, recently a plant-based nugget (PPN) counterpart with sensory and textural characteristics resembling those of meat was created.[99]

The steps used in this technique to texturize proteins are as follows:

a A frozen protein solution dispersion forms ice crystals that are parallel to the cooling surface.
b Ice crystal growth results in the creation of parallel zones that trap aligned protein molecules.
c This technique results in an extended fibrous structure because the formulation ratio between the protein content and moisture content is unaltered.
d By freeze-drying the water/moisture out, a dry mass of hard fibrous protein is produced.

An aqua solution of lipids, stabilizers, colors, and flavors can be used to rehydrate the gel network of fibrous protein. When pea protein molecules are joined together, the resulting structure is stiffer than wheat protein. The necessary springiness is provided by the combination of two plant proteins. As a result, a meat substitute with the proper flexibility and hardness is created. The biggest disadvantage is to keep track of and manage various freezing conditions at one time.[99,100]

6.4. Shear Cell and Couette Cell Technique. The idea of flow-induced structure serves as the foundation for this unique technology. The procedure is carried out in either a conical shear cell or a cylindrical Couette cell, both of which are based on the concentric rheometer principle (Figure 4).

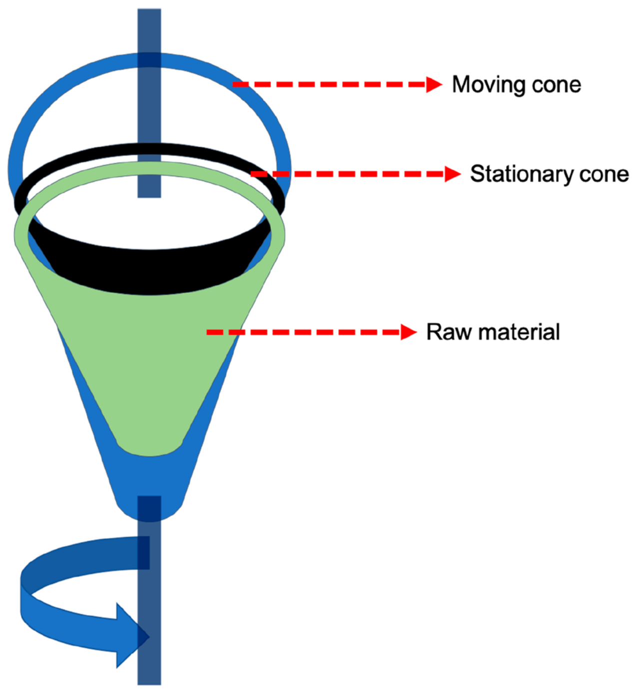

Figure 4. Conical shear cell technique and Couette cell technique.

The lower cone of the shear cell device spins, while the top cone stays stationary. A steamer or heating bath is used to regulate the processing temperature. The dough is subjected to simple shear flow and heat, which results in well-defined fibrous structures that are stable upon cooling and do not deform over time. Peighambardoust and colleagues created a Couette cell device that was utilized to successfully prepare meat analogues at high temperatures without losing structural conformance, as is seen in the extrusion technique. Additionally, the Couette cell design can be altered by enlarging the cylinder to accommodate different fiber lengths and densities. Standard spaces (shearing zones) normally have a capacity of 7 L with 30 mm space between the two cylinders, and the assembly is concurrently heated by steam and cooled by air or water. There are both unrefined and refined ready-to-eat food options on the market that can be cooked, steamed, or fried.[100] However, shear-induced structural changes can be affected by variables such as processing time, temperature, and shear rate. Utilizing this technology, anisotropic fibers were processed to create a blend of soy and pea proteins with wheat gluten. The resulting fibers

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resemble chicken fiber in mechanical strength, ranging from 50 to 100 kPa. Further studies are required to upscale this technology for commercial application.

7. NOVEL FOOD TECHNIQUES

7.1. 3D Food Printer. In order to replicate the flesh matrix seen in cattle, this technique uses computational modeling of food compositions and texture. Redefine meat, Nova meat, and Aleph Farms recently established startups that seek to develop 3D-printed plant-based meat that resembles real muscle tissue in texture and taste. The cartridge that creates a structural layer of muscle tissue is filled with the protein concentrate/isolate paste. Although there are currently no imitation steaks on the market, small-scale sensory investigations are being conducted in Switzerland, Germany, and Israel. With the help of customer ethical concerns, high-end restaurants have effectively established a niche through the widespread adoption of sustainable and nutritionally tailored alternative meat food compositions.[96,98]

Scalability, production costs, maintenance costs, spatial structure complexity, and regulatory frameworks pertaining to allergens, adulteration, labeling, and gastronomic innovation present the key challenges for 3D meat printers. The availability of labor and material supply, consumer demand, cost competition, and governmental legislation are the foundations of the business strategy for 3D food technology.[99,100]

7.2. Fermented Meat Analogue. Food formulations' flavor and functionality are enhanced by fermentation technology. Vegetable proteins use fermentation to synthesize new molecules, improving the nutritional value of goods made from plants. Specific functional proteins can be produced to make faux meat through the enzyme reformation of plant proteins in the bioreactor. For instance, Quorn's mycoprotein delivers the organoleptic qualities of meat, which has a longer shelf life and is low in fat.[97]

7.3. Soft Matter Physical Approaches. This patented method creates a stable emulsion in a colloidal solution by combining water, hydrocolloids (such as sodium alginate and methylcellulose), and plant proteins. The divalent metal cations coagulate when casein is added, forming a fibrous structure. This method guarantees that the hydrocolloid concentration in the micellar casein cationic solution is modulated in order to create a fiber. However, the textural makeup of the flesh analogue can change due to the precipitation of metal ions.

Leucine, isoleucine, and valine, three necessary branched chain amino acids (BCAAs), are abundant in pea protein isolates, which are offered in powder form and act as an immediate energy supply to the body.[100]

Cannabis plant seeds are a rich source of fiber, Fe, Zn, Mg, and α-linolenic acid (ALA), the plant form of ω-3 fat. Hemp protein, however, is not a complete protein (poor in EAA lysine).[99]

Pumpkin seeds are a significant source of protein and good fat in their complete form. However, the processing of pumpkin powder makes it low in fat and calories. It is not regarded as a source of complete protein due to low levels of EAA, threonine, and lysine, although it contains sufficient levels of minerals including magnesium, zinc, and iron as well as antioxidants and anti-inflammatory plant chemicals.[98,99]

Spirulina is a nontoxic blue-green alga that is frequently used as a vegan protein source (55−70%) and is a good source of phycocyanin pigment, which has anti-inflammatory, anticancer, and antiaging properties. It also boosts the immune system, lowers LDL cholesterol, blood sugar, and triglyceride levels, and has antioxidant and anti-inflammatory properties. By boosting ribonucleic acid and decreasing liver fat, spirulina is extraordinarily effective at protecting the brain. It contains a variety of elements in high concentrations, including minerals like magnesium and potassium as well as vitamins like B1, B2, and B3.

The star-shaped Peruvian sacha inchi seeds are the source of sacha inchi protein. It is an expensive but decent source of all EAAs except lysine, and it is particularly strong in arginine and ALA. *Salvia hispanica*, a native plant of South America, produces seeds that are used to produce chia protein.[100] Chia protein is well utilized in nutritionally balanced preparations such as smoothies, porridge, and baked goods. The high concentration of antioxidants, vitamins, and minerals—including biotin and chromium—along with the low level of EAA lysine and high dietary fiber contribute toward its easier digestibility.

Given that it is a decent source of all EAAs except lysine and contains a significant amount of BCAAs, sunflower seed protein is offered as a vegan protein powder and encouraged for use in fitness regimens.[101]

7.4. Cultured Meat. Cultured meat, often known as "in vitro meat" or "clean meat", offers an alternative to traditional meat replacements such plant-based meat, insects, algae, and pulses. It also holds the promise of a sustainable future for the environment. A key component of its widespread popularity is consumer perception. Both quantitative analysis and qualitative studies are being done to boost the acceptance of cultured meat.[100,101]

Cultured meat is a form of cellular agriculture that produces meat in vitro using a bioreactor and a culture medium. The utilization of food technology procedures aids in simulating typical cell-development activities that take place within an animal's body. Given that they might not be familiar with the processes and technologies, consumers may be sceptical about the use of biotechnology in the production of modern food. Health risks, detrimental environmental effects, and unknown long-term effects are the major concerns for consumers before completely accepting the cultured meat.[101,102] Tissue engineering is frequently the subject of ethical discussion in in vitro manufacturing. Because it avoids slaughter and relies on natural processes, the method used to produce cultured beef may be regarded as desirable and morally superior.

The quality of cultured meat must be adjusted to mimic traditional meat. Taste, texture, aroma, and appearance all have a big impact on how others react to them. One of the problems with cultured meat is that it lacks the myoglobin protein, which gives meat of animal origin its red color. To solve this problem, cultured meat can be produced using natural dyes (such sugar beet or saffron) or hemoglobin derived from animal blood or its derivatives. The functionality of muscle stem cells in scaffolds is increased by the inclusion of calm muscle cells and the sensory quality. The longevity of manufactured meat is also improved, according to recent research.

However, consumers around the world hate cultured meat, and they are quite repulsive toward it, due to their claim of cultured meat as unnatural.[102,103] As a result, the consumer may be more receptive to this technology if it has improved functioning and is emphasized for its benefits. Because cultured meat is not muscle meat, marketing strategy also affects how well it is received by consumers.[102] Before purchasing cultured meat, the consumer considers aspects like unnaturalness, healthfulness, texture, cost, and safety. Since cultured beef is rumored to have more sustainability and safety benefits, these attributes

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must be extensively promoted to increase consumer acceptance of transformed products.[104]

8. CONCLUSION

As it strives to feed a growing population of over 10 billion people by 2050, the global food system will face unprecedented challenges in the coming decades. The demand for ethical food production that considers climate change and environmental concerns is greater than ever. With its technological advancements, the Fourth Industrial Revolution presents a potential solution to transform the food system and meet these challenges. Alternative proteins, such as cultured meat and plant-based meat substitutes, are gaining momentum as potential solutions to reduce the environmental impact of meat production while simultaneously encouraging healthy diets.

Despite being proposed for many years, PBMAs have only recently gained popularity in the food and academic world. The driving causes for PBMA development, a brief history of its advancement, important technologies required for production, and the consequent consumer attitudes are summarized with the aim of examining the current position of scientific research on PBMAs and predicting future research potential. Concerns about the environment, human health, and animal welfare are what primarily influenced the development of PBMAs. Extrusion and shear cell procedures are two commonly studied structuring techniques, but for PBMA manufacturing, it is also crucial to optimize the overall flavor and appearance, control biological and chemical safety, and choose the right protein sources. Although still inadequate, customer acceptance of PBMAs is growing. Future research opportunities based on this knowledge include developing more efficient consumer education strategies, providing more scientific evidence for the health properties of PBMAs, finding more appropriate protein sources to improve the quality of the finished products, improving the appearance and flavor, further examining and securing the chemical safety, exploring the structure formation mechanism during the extraction or shearing processes, and developing a mechanistic understanding of the structure formation process.

However, there are obstacles to overcome, such as consumer acceptance, regulatory concerns, and possible threats to livelihoods in specific regions. It is critical that switching to meat substitutes and reducing meat consumption be approached with care for the health and well-being of vulnerable populations and those who rely on livestock for a living. A more sustainable and healthy food system for the future is possible with a holistic strategy that brings together innovation in technology, outreach to customers, and socioeconomic considerations.

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Notes

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