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NEXT-GENERATION MEAT ALTERNATIVES FOR SUSTAINABLE HUMAN HEALTH: A REVIEW

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ABSTRACT

The rapid increase in global meat consumption, driven by population growth and rising incomes, has intensified concerns regarding environmental sustainability, public health and animal welfare. These challenges have accelerated interest in meat alternatives, including plant-based meat (PBM), cultured-based meat (CBM), microbial protein, edible fungi, microalgae and insect-derived proteins. This review examines the historical development, production technologies, nutritional characteristics and environmental implications of these emerging protein sources. PBM has evolved from traditional soy- and wheat-derived products to highly structured analogues produced using advanced techniques such as extrusion, spinning, shear-cell processing and 3D printing. CBM offers the potential to replicate the cellular architecture of animal tissue but remains limited by high production costs, scale-up constraints, and gaps in nutritional and techno-economic data. Microbial, fungal, algal and insect proteins provide sustainable alternatives with high efficiency and unique functional properties, although challenges related to sensory attributes, pigmentation, safety and consumer acceptance persist. Overall, the future of meat alternatives will depend on advances in bioprocess engineering, protein structuring, media optimization, and rigorous sustainability assessments to support large-scale adoption.
***Keywords*:** Meat, Protein, plant-based meat, cultured-based meat, sustainability, health.

Introduction

Global meat consumption has been increasing steadily due to the increase in average income and population growth. The United Nations projects that the world population will reach 9.7 billion by 2050 (United Nations, 2019), significantly increasing the demand for nutrient-rich protein sources. Over the past two decades, global meat consumption has already increased by 58% (Whitnall and Pitts, 2019), reflecting this shift in dietary patterns. According to the Food and Agriculture Organization (FAO), the global demand for meat is expected to reach 455 million metric tons by 2050, which represents a 76% increase compared to 2005 levels (Alexandratos and Bruinsma, 2012). Similarly, the global demand for fish is projected to reach 140 million metric tons by 2050 (Waite *et al.*, 2014). Much of this growth is driven by middle-income economies such as China, while consumption in high-income countries remains stable or slightly declining and in low-income regions such as India it remains relatively unchanged (Godfray *et al.*, 2018).

Recent market forecasts also indicate a continued rise in meat production and consumption. The global meat market is estimated to grow at an annual rate of 7.35% between 2020 and 2025 (Anonymous, 2025), while average global per capita meat intake has reached approximately 122 g per day, out of poultry and pork contribute about one-third, beef about one-fifth and the rest comes from sheep, goats and other livestock sources (FAO-STAT, 2023). Projections by OECD/FAO (2021) suggest that global consumption of meat proteins will increase by 14% in the coming decade relative to the 2018-2020 average. By 2030, consumption of major meat categories is expected to grow further, with beef rising by 5.9 %, pork by 13.1% and poultry by 17.8% (OECD/FAO, 2021).

The growing global demand for meat has become increasingly concerning because conventional large-scale livestock production is strongly associated with public health risks, environmental damage and ethical issues related to animal welfare. From a human health perspective, modern animal agriculture contributes to foodborne illnesses, diet-related disorders, antibiotic resistance and the emergence of infectious diseases (Wolk, 2017; Jones *et al.*, 2013). Excessive intake of meat is associated with numerous chronic diseases, including colorectal cancer, obesity, type 2 diabetes, cardiovascular disorders, inflammatory bowel disease and even infertility (Abu-Ghazaleh *et al.*, 2021; Libera *et al.*, 2021). Several zoonotic diseases, such as Nipah virus and influenza A, have been linked to agricultural intensification and meat-processing facilities in the United States were identified as major COVID-19 outbreak sites (Jones *et al.*, 2013; Hendrickson, 2020).

Environmental impacts are also significant, as livestock production is a major source of greenhouse gas emissions, extensive land degradation and high-water use. The Intergovernmental Panel on Climate Change (IPCC) warned in 2018 that global greenhouse gas emissions must be reduced by 45% by 2030 to limit global warming to 1.5 °C, an essential target to avoid severe consequences expected with a 2.0 °C temperature rise (IPCC, 2018).

Animal welfare is another major concern, Billions of animals are slaughtered every year through direct practices such as livestock farming and fishing as well as indirectly through habitat destruction, by-catch and ecosystem disturbances linked to human food systems (Steinfeld *et al.,* 2006; Komoroske and Lewison, 2015). Furthermore, meat-based diets have been criticized for their inefficiency, high carbon footprint and potential nutritional imbalance. Collectively, these public health, environmental and ethical challenges emphasize the need to reduce reliance on conventional meat production and consumption.

Conventional meat production faces many challenges largely because its primary raw material (*i.e.,* animals) is naturally prone to issues such as disease, inefficiency and welfare concerns. When animals are removed from the production chain, many of the environmental, ethical and safety problems linked to traditional meat systems can be significantly reduced. Compounding these challenges, the special status of meat in the human diet makes it almost impossible to reduce the demand for meat products in modern society. Therefore, the production of meat alternatives, including cultured meat, plant-based meat alternatives, microbial protein, edible fungi, microalgae and insect protein has become a research hotspot aiming to ameliorate the above mentioned issues and meet the increasing demand for meat products (figure 1).

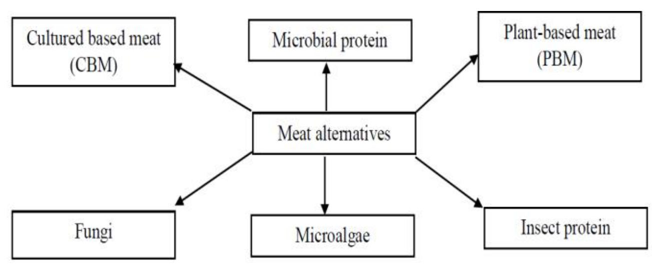

Fig. 1: Types of meat alternatives

History

Table 1: The history and evolution of animal, plant and cell based approaches to meat production.

Era / Period	Key Developments in meat alternatives	Reference
Ancient Times (206 BC-1000 AD)	Traditional PBM sources like tempeh, seitan and tofu emerged.	Shurtleff and Aoyagi, 2013
	First documentation of seitan production (900 BC-600AD)	Rubio *et al.*, 2020
	Tofu developed in China during the Han Dynasty (206 BC-220 AD).	Shurtleff and Aoyagi 2013; Rubio *et al.*, 2020
	Widespread use of tofu during Tang Dynasty (618-907 AD)	Shurtleff and Aoyagi, 2013
	Spread of tofu to Japan during the Tang and Song dynasty	Shurtleff and Aoyagi, 2013
Early 20th Century	Introduction of cereal and nut-based meat substitutes.	Shurtleff and Aoyagi, 2014
	First documentation of yuba production 1500 -1800 AD	Rubio *et al.*, 2020
	Products like *Nuttose* and *Protose* developed by John Harvey Kellogg. 1800-1900 AD	Shurtleff and Aoyagi, 2014; Rubio, *et al.*, 2020
	Emergence of Texturized Vegetable Protein (TVP) from soy isolate protein (SIP), soy protein concentrates (SPC), defatted soy meal (DSM) and wheat gluten (WG)	King and Lawrence, 2019
	Commercialization of soy and wheat-based analogues 1900-1950 AD	Rubio *et al.*, 2020
Mid to Late 20th Century (1940's-1980's)	World War II innovations boosted plant protein isolates, concentrates and dry textured proteins.	Pullen, 2018
	Development of soy-based meat analogues increased as meat demand grew.	Pullen, 2018
	Tofurky introduced in the USA in 1980.	Pullen, 2018

Early 21st Century (2000-2015)	First mainstream PBM burger launched by *Burger King* in 2002.	Green (2020)
	New PBM generation: *Impossible Burger*, *Beyond Burger*	Bakhsh *et al.*, 2025
	Improved texture, taste and appearance using extruder technologies.	Bakhsh *et al.*, 2025
Recent Era (2015-2023)	launched the first cultured meat hamburger By professor Mark Post of Maastricht University, 'the father of cultured meat' in 2013	Zhang *et al.*, 2022
	the global PBM market expanded rapidly, attracting not only vegan consumers but also regular meat eaters in North America and Europe.	Kyriakopoulou *et al.*, 2019

The plant-based meat (PBM) market is projected to grow at an annual rate of 7.9% between 2019 and 2024 with the faster-rising market being Europe and Asia (Intelligence, 2016). Overall, the international protein-based meat business will touch 21.23 billion USD$ till 2025 (Zion, 2019). At the same time, this fails compared with the global prediction 2025 of the poultry, animal meat and seafood sector, which is projected to reach US$ 7.3 trillion by 2025 (Newswire, 2019).

There are more than 50 startup companies around the world aiming to commercialize cultured meat (Guan *et al.,* 2021). For example, Mosa Meat, which was founded by Professor Post in the Netherlands recently received $75 million in funding in December 2020 and American Memphis Meats which focuses on high density culture of 'immortalized' cell lines has raised $180 million in capital. In China, Jose Future Food recently received a 20 million RMB investment to accelerate the development and large-scale production of cultured meat. The PBM and CBM sector will rise from a niche market to customer plates in the coming days (Zhang, *et al.*, 2022).

Concepts of Plant-based meat (PBM)

PMB is made from plant-based proteins that comprise high content of essential amino acids, low cholesterol and saturated fats (Guo *et al.*, 2020); it is are also called as mock meat, faux meat and meat alternatives. PBM is alternatives resemble various aspects of meat including its texture, flavour or nutritional qualities. These options span from naturally occurring foods that share certain meat-like traits (such as pulses, mushrooms and jackfruit), to traditional products that do not specifically imitate meat but can serve similar culinary purposes (such as tofu, tempeh, seitan and bean-based patties). Additionally, there are highly processed products intentionally formulated to closely replicate the sensory experience of eating meat, including items like plant-based burgers, hot dogs and fish-style fillets (Lagally *et al.*, 2017). Meat alternatives can be produced using various plant proteins such as oilseed proteins, cereal proteins, legume and pulse proteins and leaf proteins. Oilseed proteins are obtained from soybeans, rapeseed or canola, sunflower seeds, sesame, flaxseeds and linseeds and cereal proteins are obtained from wheat, corn, rice, barley, sorghum and amaranth grain (Kyriakopoulou *et al.*, 2019). These plant sources have different compositions and physicochemical and structural properties that are very diverse from those of animal ingredients, which make them difficult to mimic the structure, properties and flavour of meat or meat products (Imran and Zhang, 2023). Plant-based meat products are made from plant protein after processing by extrusion, silking, conditioning and other techniques, to mimic the texture of meat products (He *et al.*, 2020).

Since 2010, several plant-based meat companies such as 'Impossible Foods' and 'Beyond Meat', have grown rapidly and partnered with major fast-food chains such as Burger King, KFC, McDonald's and 'Starbucks'. Impossible Foods recently secured $200 million to expand its product portfolio and global reach. Beyond Meat, founded in 2009, has become one of the leading players in the sector, achieving a market value close to $10 billion. In 2019, 'Burger King' helped accelerate the plant-based trend by launching its plant-based "Royal Burgers" in the U.S. and China, signalling a major shift in the restaurant industry (Zhang *et al.*, 2022).

Sources of plant protein sources for PBM Alternatives

Although the choice of plant protein constituents is the initial stage for creating a PBM product, the choice of plant protein depends on the protein availability, protein extraction potential and yield of the crops. The most commonly used plant-based constituents were formerly by-products of the industry (mainly starch or oil manufacturing) (Imran and Zhang, 2023).

Table 2: Different types of protein used in meat analogues production

Proteins	Structural characteristics	Effects	Functionality	References
Soy protein	Soy protein isolates and concentrate mainly contain β-conglycinin (7S) and glycinin (11S). The 7S protein has three subunits, while the 11S protein is a hexamer made of	Patties produced using texturized soy protein at 130 °C and 50% moisture showed an appearance	Fibre formation, gelation and aggregation by extrusion	Fukushima, 2011; Samard *et al.*, 2021

	acidic and basic subunits linked by disulfide bonds.	similar to commercial patties.	Emulsification	
Wheat protein	Gluten is composed of proteins: gliadin and glutenin. Gliadins are low to medium molecular weight monomers with intramolecular disulfide bonds, while glutenin's are larger, multi-polypeptide proteins joined by intermolecular linkages.	Adding 30% wheat gluten improves texturization, hardness, chewiness and fibrous structure	extensibility, elasticity and fibrous texture	Chiang *et al.*, 2019
Pea protein	Pea protein consists of globulin, albumin, glutelin and prolamin. The globulin includes legumin (11S), vicilin (7S), convicilin,	patties made with pea protein isolate had a firmer texture than the beef patties	Fibre formation, gelation and aggregation by extrusion Emulsification	Shen *et al.*, 2019
Potato protein	Potato protein consists of three subunits: patatins (40–60%), protease inhibitors (20–30%) and other high molecular weight proteins (10%).	Patties with 30% potato protein showed better appearance than TVP, but caused darker colour in the patties.	Used to improve textural attributes	Lee *et al.*, 2022
Mung bean protein	Mung bean protein contains subunits: globulin (vicilin-type, ~60%), albumins (~25%) and smaller fractions of gliadin and glutelin.	Mung bean protein isolate showed higher foaming capacity (89.66%) than soy protein isolate (68.66%), indicating better for texturized meat.	Excellent gelling properties to help in constituents binding and water holding	Branch and Maria, 2017
Zein protein	Zein protein consists of four major components: α-zein (75-80%,), β-zein (10-15%,), γ-zein (10-15%,) and δ-zein.	The effects of textural chewiness, toughness and hardness on plant meat alternatives	stabilizer, anti-oxidant, give texture like chicken meat	Glusac, 2018
Hemp protein	Hemp protein consists of sub units: Edestin (60-80%) and Albumin (20- 40%)	Hemp protein absorbed lesser water and required higher denaturation temperature	emulsification, solubility, oil holding capacity and water holding capacity	Zahari *et al.*, 2020
Feba protein	Feba protein consists of subunits: legumin (11S), Vicilin (7), albumin, polyamines, glutelin	The effects on high moisture content and fudge like texture	firmness, elasticity, harder texture, high minerals and low water holding capacity	Ferawati *et al.*, 2020

Table 3: Non-protein constituents used in protein-based meat analogues preparation

Category	Constituents	Functionality	References
Fat and oils	Coconut oil, cocoa butter, soybean oil, corn oil, sunflower oil, canola oil, sesame oil, avocado oil, safflower oil	To improve flavour, texture (saturated fats), mouth feel, and nutrition (n-3 fatty acid-rich oils)	Dekkers *et al.*, 2018 Pietsch, *et al.*, 2018
Binding agents	Transglutaminase, calcium alginate, carrageenan, xanthan gum	To bind protein particles, shelf stability, moisture retention, increase volume and boil-out control	Chiang *et al.*, 2019
Thickening agents	wheat flour, oat Fiber, fermented rice flour, butter nut squash puree, carrot puree, sweet potato puree, apple Fiber, potato starch, potato dextrin, wheat starch, tapioca starch, modified corn starch, tapioca starch, guar gum, gum Arabic, inulin, maltodextrin, lecithin	To bind water and immobilize fat, improve rheology, texture and consistency, reduce syneresis and emulsify oils	Fernández-López *et al.*, 2020 Arora *et al.*, 2017
Flavouring agents	Sodium chloride, potassium chloride, sodium inosinate and guanylate (nucleotides), soy sauce, cane sugar evaporated cane syrup and molasses, dextrose, lactose, mannitol, vinegar, succinic acid, lactic acid, lemon juice, onion powder, celery, walnuts, oats, mushrooms, yeast extract	To boost product flavour (aroma and taste) and simulate processed meat flavours	Guo *et al.*, 2020
Colorants	Leghaemoglobin, beet juice extract, pomegranate fruit powder, caramel colour, canthaxanthin, lycopene, malt, cumin and annatto	To render red and other colours or to enhance brightness (titanium dioxide)	Schreuders *et al.*, 2019

Current Advancements to Create Plant-Based Meat

An important part of meat alternative production is that alternative meats should be made physicochemical and textural properties closed to real meat (Zhang, *et al.*, 2022). The key requirement to produce meat analogue is the proper textural profiling which resembles the meatiness. The novelty of the product depends on various ingredient compositions that are worked in sync with extrusion conditions. Plant proteins are first selected and pre-treated, then processed through extrusion to create a fibrous, meat-like structure. After this, flavour enhancers, seasonings and colourants are mixed and the material is shaped and finished into the final food product (Zhang, *et al.*, 2022) (figure 2). There are several methods used for textural profiling; the commonest are spinning technique, extrusion cooking under high and low-moisture content and the newest shearing technology using shear cell and Couette cell, Freeze structuring by stretching extrudate using flow-induced structuring (Singh *et al.*, 2021).

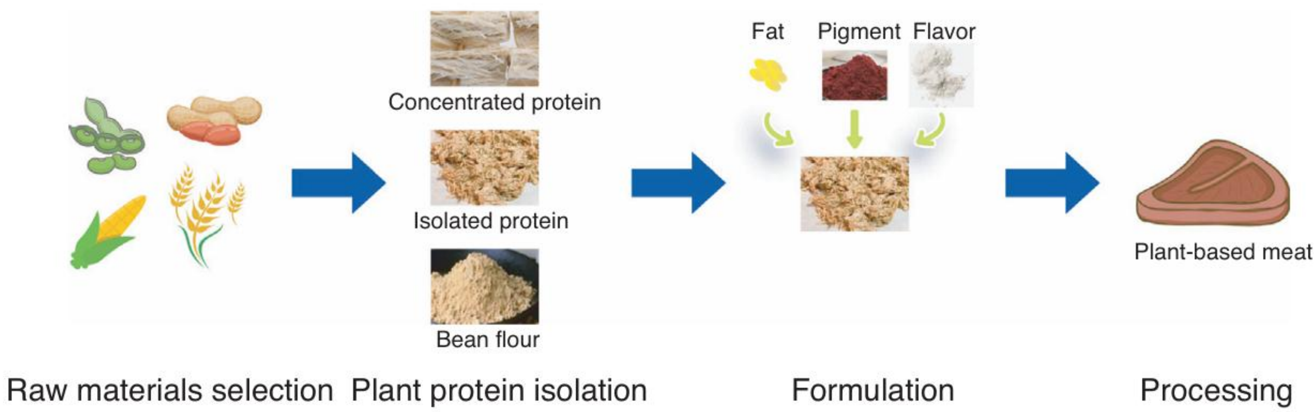

Fig. 2: Systematic diagram for protein-based meat production (Zhang, *et al.*, 2022).

Extrusion technique

Extrusion technology combines water, heat and mechanical force to produce meat alternatives. During this process, proteins are reshaped into fibrous structures as they pass through heated, pressurized extruders. The resulting protein fibers serve as versatile raw materials for making a wide range of plant-based meat products (Lee *et al.*, 2022) (figure 3).

In an extruder system, the main components include the preparation unit, feeder, barrel, screw, die and cutter. During processing, the prepared or dried ingredients with the right moisture level are fed into the machine. As the material moves from the feeder toward the screw, it is mixed, aligned, and pushed into the compression zone. In this zone, the screw depth and pitch decrease, increasing pressure, temperature and shear. These changes transform the ingredients into a molten, paste-like mass. Just before exiting the extruder, the product reaches very high temperature and pressure and once it leaves the die, its viscosity drops sharply (Imran and Zhang, 2023). Extrusion is a versatile processing method that involves several steps, including mixing, hydrating, homogenizing, removing air, applying shear, heating, expanding, shaping and compressing the ingredients. When carried out at moderate to high moisture levels (40–80%) and elevated temperatures (140–180 °C), the process creates a fibrous texture by texturizing the proteins under shear. During extrusion, proteins undergo micro-coagulation and fibrillation and their unfolded molecules easily cross-link to form fibers. However, these fibers are anisotropic and still do not perfectly match the structure of real muscle tissue. Natural muscle fibers have a highly unique and complex arrangement, giving meat its characteristic qualities such as texture and water-holding capacity. The processes can be summarized in three steps (Singh *et al.*, 2021):

a. Pre-conditioning of the material outside the extruder

b. Mixing or cooking inside the extruder barrel

c. Cooling in the die

Extrusion methods are generally divided into high-moisture and low-moisture processes, depending on how much water is added during extrusion to form the meat analogue.

In low-moisture extrusion, the textured meat analogue is rehydrated (< 30%) before cooking or fried. The food product is similar to a sponge and absorbs the water quickly once dipped in cream. It is preferably used as a meat extender in sausages and beef patties (Riaz, 2021).

In high-moisture extrusion also called wet extrusion, the texturized chunks are well hydrated (more than 50%) during the extrusion process, followed by freezing to maintain the moisture content. In after pre-conditioning of the raw material, the twin-screw rotator increases the processing temperature up to 130-180 °C due to the dissipation of mechanical energy. Ultimately, the protein starts melting in the extruder barrel, after which the viscoelastic mass is exposed to the long cooling die. This leads to creating structural aligned texturized proteins, prevents food material expansion of newly formed structure and easily packed in wet conditions into pouches, cans or frozen (Maurya and Said, 2014).

Extrusion is multi-functional technique and most economical, as the food quality and productivity are consistent throughout the food processing. It is easy to operate and clean, saves water, energy and a variety of raw materials can be processed. The main challenges that occurred in this technique are changes in colour due to the Maillard reaction, caramelization, hydrolysis and degradation of pigments.

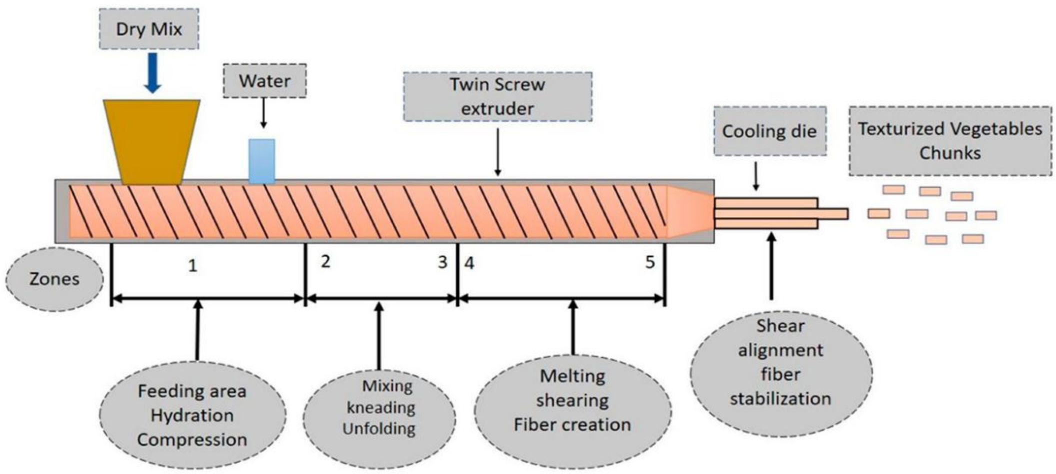

Fig. 3: Systematic diagram of extrusion method (Zhang *et al.*, 2022).

Spinning technique

A more advanced method for making meat alternatives involves spinning concentrated plant proteins at high speeds to create thin, meat-like fibres. Although effective, this technique is sensitive, costly and requires large amounts of acidic or alkaline solvents, which also produce significant waste similar to how textile fibres are manufactured (Singh *et al.*, 2021) (figure 4). Two types of spinning technologies are electrospinning and wet spinning, depended on the biopolymer solutions alignment for PBM product formation (Manski *et al.*, 2007). In Wet spinning, a thick protein polymer solution is pushed through a spinneret to form stretched, aligned fibres. These fibres are then solidified in a coagulation bath containing acids, salts or alkalis. The fibres must be thoroughly washed afterward, which creates a large amount of wastewater as a by-product (Imran and Zhang, 2023).

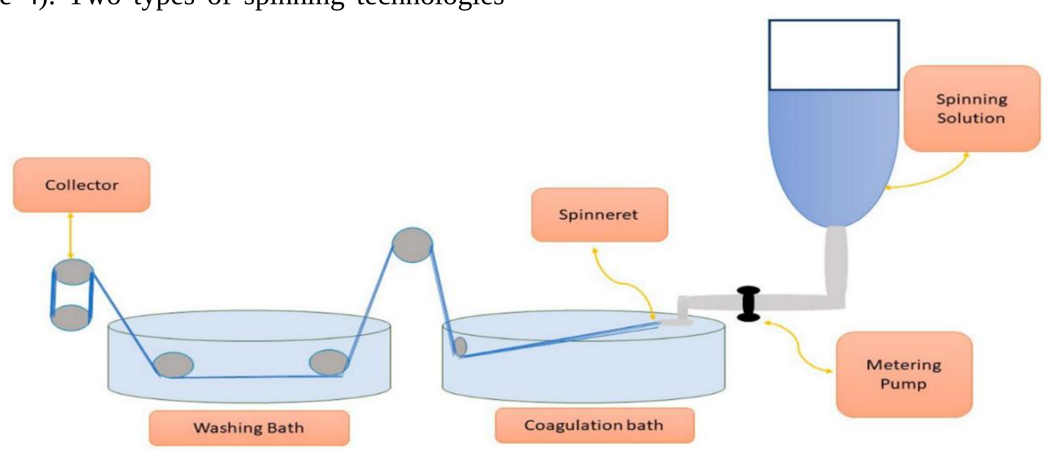

Fig. 4: Systematic diagram for wet-spinning process (Imran and Zhang, 2023).

Electrospinning has emerged as a promising alternative technique. In this process, a high voltage is applied to a suitable polymer protein solution, producing extremely thin, high aspect ratio fibres at the nanometre scale. To work effectively, the solution must meet key criteria such as proper conductivity, solubility, viscosity, surface tension and the ability to form entangled chains. When these conditions are met, the solution forms a Taylor cone and the charged jet is drawn toward a metal collector, creating fine, swirling fibres. As the solvent evaporates during spinning, it leaves behind delicate, breathable fibres made of intertwined polymers (Schiffman and Schauer, 2008) (figure 5).

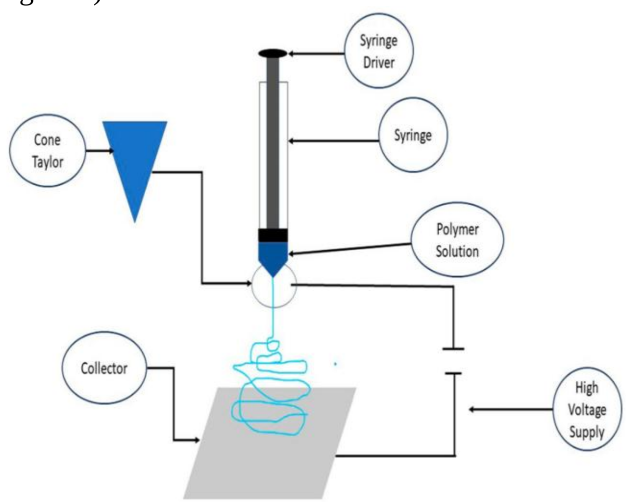

Fig. 5: Systematic diagram for electrospinning process

Shear cell and Couette cell technique

This is an emerging technology that relies on flow-induced structuring of proteins. It is carried out using either a shear cell (a conical device) or a Couette cell (a cylindrical device). Both systems operate on the principle of a concentric rheometer, where controlled shear forces help align and structure the material (Manski *et al.*, 2007) (figure 6).

In a shear cell, the bottom cone rotates while the top cone stays still and the temperature is controlled using a steamer or heating bath. The combination of heat and steady shear forces helps the protein dough develop clear, fibrous structures that remain stable after cooling and do not deform easily. (Manski *et al.*, 2007; Peighambardoust *et al.*, 2007). Couette cell system can form meat analogues at high temperatures while maintaining a consistent structure something that is often difficult to control with extrusion. The design can also be adjusted by enlarging the cylinder to achieve different fibre lengths and thicknesses. Typically, the shearing zone holds about 7 lit of material with a 30 mm gap between the inner and outer cylinders, and the unit is heated with steam and cooled with air or water. Various ready-to-eat products made using steaming, cooking or frying are already available. However, the final fibre structure depends heavily on processing time, temperature and the applied shear rate. Generally, the standard space (shearing zone) has a volume of 7 lit and a 30 mm distance between the two cylinders, heated simultaneously by steam and cooled using air or water. In the market, both unrefined and refined ready-to-eat food products by steaming, cooking or frying are available. However, factors such as processing time, temperature and shear rate can alter the shear-induced structuring (Krintiras *et al.*, 2015). This method is relatively low-cost and can produce larger, soft, fibrous meat analogues. It has been used to create anisotropic fibres from pea protein–wheat gluten and soy protein–wheat gluten blends, resulting in fibres with a mechanical strength of 50-100 kPa close to that of chicken muscle. However, further research is still required to scale this technology for commercial production (Singh , *et al.*, 2021).

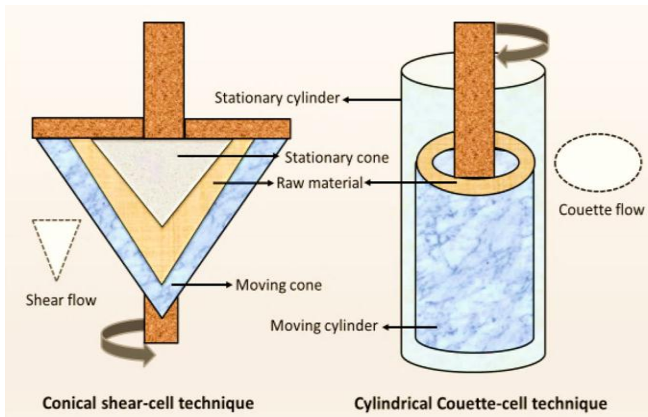

Fig. 6: Conical shear cell technique and cylindrical Couette cell technique

Freeze structuring technique

Production of fibrous meat analogues is possible through freezing structuring, but it is very sensitive to the source of protein types and characteristics (such as gelation, solubility and water holding capacity) and freezing or drying conditions (such as time and temperature). During freezing structuring, proteins are mixed with other ingredients until a uniform emulsion is formed. The final mixture is prepared, frozen (to make ice layers) and then dried by frying, baking or steaming (Yuliarti *et al.*, 2021). Textural characteristics of proteins can be controlled through changing conditions of freezing such as effects of heat exchange, effects of pressure, rate of freezing, surface effects, the solid content of material and pH. The main disadvantage of freeze structuring technique is to control and optimize different freezing condition at provided time (Imran and Zhang, 2023).

3D-printing technology

The emerging technique of 3D printing or additive manufacturing, is increasingly being explored as a novel approach for creating muscle-like structures from plant proteins. In this method, protein powder is blended with water to form a printable paste, which is then deposited layer by layer, producing fibres that closely resemble those found in animal muscle (Dankar *et al.,* 2021) (figure 7). To achieve the desired texture, rheological properties and firmness, enzymes such as transglutaminase and other functional additives are often incorporated during the printing process, helping to generate a product with a more authentic meat-like appearance. Companies such as Novanet are already utilising this technology to manufacture 3D-printed beef-style steaks and other plant-based meat analogues, replicating the look, texture, flavour, and nutritional profile of conventional meat (Lipton *et al.,* 2010).

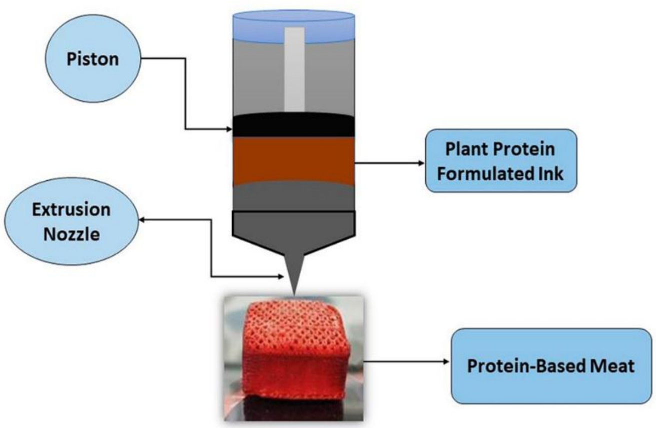

Fig. 7: Systematic diagram for 3D-printing technology for PBM

Cell Type for Cultured Meat

Cultured meat or Cell Types for Cultured Meat or lab grown meat is considered the most promising meat alternative, since animal-based proteins can be obtained directly from ex vivo cultivation of stem cells without raising and slaughtering animals (Weele, *et al.,* 2019). Cultured meat provides a more sustainable and environmentally friendly alternative to traditional meat production with similar flavour, taste and nutritional profiles, so it is a potentially revolutionary meat production technology (Choudhury *et al.,* 2020).

More than 50 startup companies across the globe are now working to bring cultured meat to the market. For instance, Mosa Meat in the Netherlands, founded by Professor Post, secured about $75 million in funding in December 2020. Similarly, the American company Memphis Meats, which specializes in high-density cultivation of *immortalized* cell lines, has raised nearly $180 million. In China, Jose Future Food also received an investment of 20 million RMB to speed up the development and large-scale production of cultured meat. Despite this growing interest and financial support, the cultured meat industry is still at a very early stage. Two of the biggest challenges that limit large-scale production are the need to develop animal-free culture media and to design large, affordable bioreactors. These hurdles must be overcome before cultured meat can be produced efficiently and at a commercial scale (Zhang *et al.,* 2022). The production process for cultured meat can be roughly divided into three stages (Zhang *et al.,* 2022) (figure 8):

(1) Raw material preparation: isolating animal stem cells and preparation of in vitro culture medium.
(2) Tissue culture: the proliferation and differentiation of stem cells, carried out in large bioreactors, to form muscle fibers and tissues.
(3) End product processing: the obtained muscle tissues or muscle cells are processed into the required meat products.

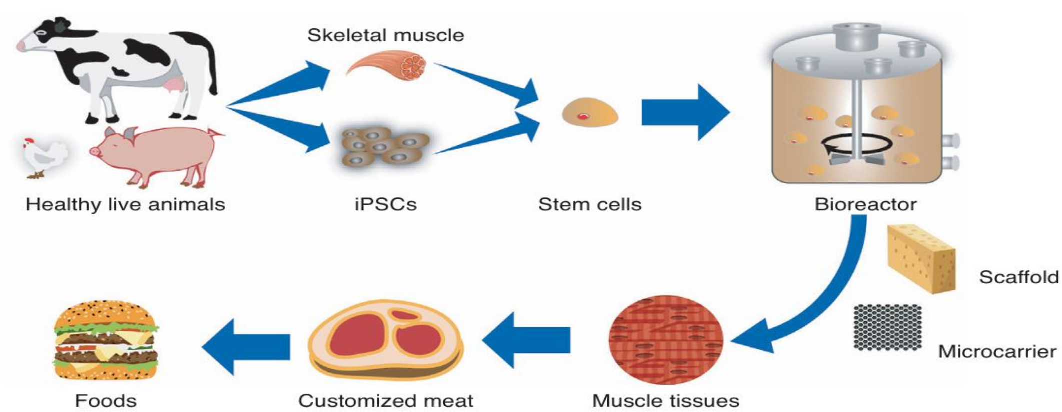

Fig. 8: Schematic diagram of the cultured meat production process (Zhang *et al.,* 2022).

Stem Cell Isolation

Cultured meat production begins with selecting cell types that can both multiply sufficiently and transform into the mature cells that make up edible meat. Because these characteristics are essential, stem cells are the preferred starting material.

Stem cells are generally divided into two major categories such as pluripotent stem cells and adult stem cells. Among these, adult stem cells, which act as undifferentiated progenitors located in specific tissues and more commonly used for cultivated meat (Ryu *et al.,* 2023). Their multipotent nature allows them to develop into several essential cell types required for muscle tissue formation. there are three main cell types such as muscle satellite cells, mesenchymal stem or stromal cells (MSCs) and fibro or adipogenic progenitors (FAPs). Out of these, muscle satellite cells have received the most attention. They are abundant in adult muscle tissue (Bentzinger *et al.,* 2012) and can be isolated efficiently from livestock such as cattle, pigs and poultry (Stout *et al.,* 20220). Because they are easy to obtain and possess strong myogenic differentiation ability, muscle satellite cells are considered one of the most suitable sources for cultured meat. However, muscle tissue contains many other cell types such as fibroblasts, endothelial cells and blood cells. Which are challenging to isolate a highly pure population of muscle stem cells (Zhang *et al.,* 2022). To address this, fluorescence-activated cell sorting (FACS) is commonly used to purify the desired progenitor cells. Although adult stem cells are accessible and capable of producing the mature cell types needed in meat, their proliferation capacity and long-term maintenance in vitro are still limited. Additionally, FACS requires costly antibodies, which makes it less feasible for industrial-scale production (Zhang *et al.,* 2022).

Pluripotent stem cells (PSCs), are similar to totipotent stem cells, with self-renewal and multi-directional differentiation potential Because of these traits, they are widely used in the medical field and may offer a practical solution (Zhang *et al.,* 2022). Pluripotent stem cell-relevant cell types can be divided into embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs). Embryonic stem cells can produce cultured meat with the same quality since they have an infinite proliferation ability while maintaining differentiation if they become like cells. Although they have advantages, ESCs are difficult to culture and it is challenging to scale-up their application due to high costs. ESCs themselves are difficult to obtain and cell maintenance. iPSCs can be obtained from somatic cell reprogramming such as overexpression of pluripotent transcription factors and small molecule mediated reprogramming. The cells differentiate into several types and they are simpler and easier to obtain than ESCs (Liu *et al.,* 2021).

Economical culture medium

Ex vivo expansion of muscle stem cells is a crucial step in producing cultured meat. However, their ability to multiply drops as the cultivation time increases. This happens because repeated cell division shortens their telomeres, leading to genome instability and eventually causing the cells to undergo programmed cell death (apoptosis).

The culture medium provides all the nutrients needed for cells to grow outside the body, and fetal bovine serum (FBS) is one of its key ingredients. However, producing FBS is considered inhumane and involves a complicated process, which greatly increases the overall cost of the culture media (Choudhury *et al.,* 2020). Therefore, the development of serum-free media will be more helpful to reduce costs. Bioengineering technology can be used to synthesize proteins or on nonanimal extracts, so as to greatly reduce the cost and improve the stability of media (Zhang *et al.,* 2022).

Structuring Methods in Cultured Meat Production:

The production process or techniques for cultured meat have been developed using a selection of animal sources and various production factors for cell types including different media, scaffolds, carriers, bioreactors and 3D bio-printing.

The 3D printing process in cultured meat contributes to the production of highly structured meat products as compared to conventional meat. In addition, 3D-printed cultured meat has the potential to appeal to specific populations who experience significant challenges with food digestion or nutritional intake, such as individuals suffering from dysphagia. 3D printing technology can especially help solve the problem of creating meat-like textures, as it can regulate the protein, fat and nutritional components. 3D printing is used to create bovine satellite cell maturation by harnessing the tissue as well as retaining cell viability. use of bio-printing and they found that bovine cell fibers including muscle, fat and vessel were collected to produce in vitro construction of engineered, steak like meat tissue. Fabricated steak-like meat is produced by muscles, adipose tissues and blood capillaries (Maung *et al.,* 2021; Ianovici *et al.,* 2022).

The use of a scaffold also leads to the generation of a fibrous structure for meat alternatives. The scaffold used may be separated after cells grow or may be used to produce cultured meat using an edible scaffold. Scaffold materials can be divided into those naturally derived from plants or animals and those made out of synthetic materials (Lee *et al.,* 2022).

Another technology for developing a meat-like structure is the use of a microcarrier on a culture device (bioreactor type). Microcarriers for upscaling cell cultures are commonly used in combination with bioreactors and they are mixed with culture media in the bioreactor. The physical properties of the surface are designed to be like those of the extracellular matrix so that the cells are well attached. numerous microcarriers have been developed, such as cytodex 1, cytopore 1 & 2, cytoline 2, plastic plus, FACT III, and collagen Microcarriers have been mainly used for plastic materials and currently, they make edible materials such as dextran and gelatin (Bodiou, *et al.,* 2020).

Insect Protein

Insects have long been part of the human diet, especially in many Asian and African cultures. (Ramos-Elorduy, 2009). The Food and Agriculture Organization (FAO) reports that more than 1,900 insect species are eaten globally. (vanHuis *et al.,* 2013). This practice, known as entomophagy, is considered sustainable because edible insects provide high levels of protein and healthy polyunsaturated fats, although the exact nutrient content varies by species. Insects also convert feed into edible body mass far more efficiently than traditional livestock, making them an environmentally friendly food source (Raksakantong *et al.,* 2010).

Insects are increasingly recognized as sustainable and environmentally friendly sources of protein, offering several clear advantages over traditional livestock. They are affordable to produce because insect farming requires minimal resources and many species can be mass produced thanks to their high reproductive rates and efficient feed conversion. Insects also create far fewer greenhouse gas emissions and demand much less land and water, making them an attractive option for reducing the environmental footprint of food production. Nutritionally, they provide a rich supply of protein, vitamins, fiber, healthy fats and essential minerals. As a result, major companies such as ‘EnviroFlight’ and ‘Agriprotein’ in the United States, ‘Haocheng Mealworm Inc.’ in China, and emerging brands like ‘Bitty Foods’, ‘Bugsolutely’ and ‘Grilo’ are actively investing in research and development to expand the potential of insect-based foods (Lee *et al.,* 2022).

Table 4: Major groups of insects consumed around the world (vanHuis *et al.,* 2013).

Insect order	Insect Species
Coleoptera	Yellow mealworm (*Tenebrio molitor*), palm weevil (*Rhynchophorus phoenicis*, *Rhynchophorus ferrugineus* and *Rhynchophorus palmarum*)
Lepidoptera	Caterpillars of butterflies or moths (*Daphnis spp., Theretra, Imbrasia belina, Omphisa fuscidentalis, Comadia redtenbacheri* or *Aegiale hesperiasis*)
Hymenoptera	Weaver ants (*Oecophylla spp.*), yellow jacket wasps (*Vespula* and *Dolichovespula spp.*) and honeybees (*Apis mellifera*)
Orthoptera	Crickets (*Gryllus bimaculatus* and *Acheta domesticus*) and locusts (*Locusta migratoria*)
Hemiptera	Cicadas (*Ioba, Playtypleura* and *Pycna*), pentatomid bugs (*Agonoscelis versicolor*)
Isoptera, Odonata, Diptera and others	Termites (*Macrotermes* and *Syntermes*), dragonflies, flies, ants and others

There are three processing technologies are required for raw material processing, protein processing and oil processing (Dossey *et al.,* 2016).

Among the technologies studied for the development of edible insects, raw materials processing technologies of drying and powdering are the most widely used method for applying insects to food. these methods reduce the size and moisture content of the insects, making the resulting powder easier to transport and suitable for long-term storage. The low water activity not only enhances flavour and overall product quality but also improves microbial safety and supports the formation of beneficial bioactive compounds (Hernández-Álvarez *et al.,* 2021).

Drying processing technologies are sun drying, oven drying, smoke drying, freeze drying and roasting. For edible insects, their treatments vary, including thermal blanching, pulse electric field and microwave-assisted drying. The freeze-drying process involves drying the frozen water in an insect sample by eliminating the ice by sublimation and this process is not affected by pressure and heating (Hernández-Álvarez *et al.,* 2021). Low-temperature processes, such as freezing and refrigeration, have the advantage of maintaining the appearance and sensory characteristics of the food and make only minor changes in the proximate composition (Hernández-Álvarez *et al.,* 2021)

Protein and oil processing technologies have been studied that use insect components while diminishing negative effects from external characteristics (such as perceptions that they are dirty, disgusting, and dangerous). Supercritical CO_2 extraction, which is a non-conventional extraction method, has advantages such as reduced oxidation of solutes, extraction of heating sensitive ingredients by low temperature process and modulation of solvent selectivity by modulating conditions (Purschke *et al.,* 2017).

Single-Cell Protein: Microalgae, Fungi and Bacteria

Microalgae:

Algae have been part of the human diet for centuries. While macroalgae like kelp and nori are traditionally eaten as vegetables, they have also gained use in recent years as feed ingredients for livestock. Microalgae, which exist as single-celled organisms, are particularly valued for their impressive nutritional profile, they contain about 60-70% protein (on a dry weight basis) and are abundant in long-chain polyunsaturated fatty acids, carotenoids and various other bioactive compounds (Jones *et al.,* 2017). More importantly, microalgae possess a highly efficient photosynthetic system that allows them to convert light, carbon dioxide and water into oxygen and carbohydrates. This natural efficiency, combined with their low production cost, makes microalgae a promising resource for developing future meat alternatives.

Certain microalgae and cyanobacteria are primary producers of microbial oils such as the omega-3 fatty acids eicosapentaenoic acid (EPA) (Karnaouri *et al.,* 2020) and docosahexaenoic acid (DHA) (Thiyagarajan *et al.,* 2020). Microalgae are currently utilized in the food industry primarily as functional additives. Studies have shown that incorporating 30-50% spirulina during the extrusion of soy protein does not alter the final product's structure and can enhance its flavour under low-moisture conditions. However, excessive inclusion of spirulina may adversely affect both the flavour profile and the visual appearance of the product.

The development of microalgae as meat alternatives is constrained by several key factors, particularly their intense pigmentation and the challenges associated with harvesting and large-scale production. The natural colour and characteristic fishy odour of microalgae are difficult to eliminate and often result in products that are visually unappealing, representing a major barrier to their use in food applications. Furthermore, microalgal proteins typically contain lower levels of essential amino acids such as methionine, cysteine, lysine and tryptophan compared to meat proteins and they also exhibit reduced digestibility. Nevertheless, microalgal protein is still a useful additive to meat alternatives and has great potential to be improved (Loveday, 2019).

Microbial proteins

Microbial proteins (MPs) provide all eight essential amino acids, including lysine an amino acid often limited in plant-based proteins thereby offering high nutritional value. In addition, MPs possess several advantages, such as a wide variety of suitable microbial sources, rapid growth rates, and high production efficiency. After appropriate processing, including cell wall disruption and nucleic acid removal, these proteins can be rendered suitable for human consumption. Although efforts to incorporate MPs into food products began as early as the 1980s, their adoption was limited at the time due to high production costs and the then nascent stage of fermentation technology (Matassa *et al.,* 2016).

Although microbial proteins are nutritionally rich, they are not composed of pure protein, instead, they contain various other cellular components that may pose potential food safety concerns. In particular, certain yeast and bacteria derived proteins have elevated levels of nucleic acids, especially RNA, which can be problematic if not properly reduced during processing. (Patthawaro and Saejun, 2019), therefore, further research is required to develop effective technologies for nucleic acid removal. In addition, some microbial proteins may contain toxic contaminants, particularly when grown on media derived from petroleum sources, such as aromatic compounds or methanol. This highlights the need for careful selection and regulation of culture media used in MP production. Advancing the use of microorganisms as efficient hosts for generating nutritionally complete, safe, and cost-effective microbial proteins will be a key focus for the future development of the meat substitutes industry (Zhang *et al.,* 2022).

Edible fungi

Edible fungi are ideal meat alternatives, because of their high protein and dietary fiber content, and low-fat content. The high content of sulphur-containing amino acids in some edible fungi enables the production of a meaty flavour. Edible fungal proteins can be obtained from *Lentinus edodes, Pleurotus ostreatus, Agaricus bisporus, Flammulina velutipes* and *Pleurotus eryngii*. The production cost of edible fungal protein is lower than that of bacterial, animal or plant protein (Schweiggert-Weisz U), some large edible fungi are easy to cultivate and harvest and the cultivation technology of some large fungi is very mature. In addition, edible fungal proteins have beneficial biological activities and are widely recognized by consumers for their safety and health benefits, with high market acceptance. The global market for mycoprotein products continues to gain impressive momentum, with global sales estimated to grow nearly twofold by 2027, compared with 2019, at a compound annual growth rate (CAGR) of more than 12% and sales estimated to exceed US$500 million by the end 2027 (Zhang *et al.*, 2022).

Advantages and disadvantages

Table 5 : Advantages and disadvantages of various meat alternatives

Meat alternatives	Advantages	Disadvantages
PBM	• Low cost of producing price • Contribution to solve environmental crisis such as resource depletion and GHG's emissions and problem of animal welfare (Santo, *et al.*, 2022). • It increased protein contents, whereas decreased cholesterol and blood pressure • Do not cause food poisoning that be able to occur in livestock meat production (Rubio *et al.*, 2020).	• Gluten or genetically modified organism of raw materials in plant protein • Some consumers feel that textural sensory is low compared to real meat (Starowicz *et al.*, 2022)
Cultured meat	• Lower land use, GHG emissions and freshwater use than meat production (Mottet *et al.*, 2017). • Nutrient composition can be improved like polyunsaturated fatty acids, omega-3 and iron does not cause any allergenic reaction (Roy *et al.*, 2021). • Reduction in zoonotic and food borne disease (Lee *et al.*, 2020)	• Price of cultured meat is still higher than traditional meat (Ye *et al.*, 2022). • Use of fetal bovine serum is related to ethical concern leading the foetus to death (Mottet *et al.*, 2017). • Limited market products (consumer anxiety) • Potential safety risks from unknown processing substances
Insect-based meat	• Insects have a high fecundity rate thus good mass production • Solve problems such as environmental pollution, animal welfare • High nutritional contents (proteins, Fe, Zn, Na, Ca, riboflavin and biotin etc.,) (Kouřimská and Adámková, 2016)	• Low acceptance due to food neophobia or a negative perception in terms of dirty, dangerous, disgusting, and unhygienic (Lee *et al.*, 2020; vanHuis, 2013)

Environmental sustainability

Food processing undeniably places significant pressure on the environment. It contributes an estimated 70-80% of the global water footprint and is responsible for nearly 30% of worldwide greenhouse gas emissions (Smetana *et al.*, 2015). Greenhouse gas emissions, water consumption, eutrophication potential and land use associated with cultured meat are all lower than those of conventional livestock production. However, cultured meat currently requires considerably more energy to produce (Tuomisto and Mattos, 2011; Mattick, *et al.*, 2015). Both Beyond Meat® and Impossible meat™ Foods have published life cycle assessments (LCA) for their plant-based beef alternatives. These assessments show that the eutrophication potential and land use of their products are substantially lower than those reported for conventionally farmed beef, pork, and chicken. Their greenhouse gas emissions fall between the levels typically associated with pork and chicken, while their energy use is higher than that of both. In comparison, mycoprotein products such as Quorn™ have greater energy demands and higher emissions than Beyond and Impossible™ products, but they require less land to produce. Comparative analysis of various alternative protein sources and reported that cultured meat exhibited the greatest environmental impact particularly in terms of carbon emissions and water use, even after accounting for differences in caloric and protein content (Heller and Keoleian, 2017). In contrast, insect-based proteins required the most land area for production, exceeding the land demands of both mycoprotein and cultured meat (Smetana *et al.*, 2015). The first relevant LCA published in 2011 Est involve lower energy consumption (7-45%), greenhouse gas emissions (78-96%), land use (99%) and water use (82–96%) compared to animal based meat (Tuomisto and Mattos, 2011). A 2015 life cycle assessment of cultured beef meat (CBM) presented more modest reductions in environmental impacts. The study found that CBM could have higher energy use, acidification potential and ozone depletion impacts than animal-based meat, particularly when compared with poultry production (Mattick *et al.*, 2015). cultured beef meat (CBM) is estimated to achieve a 47% energy feed conversion efficiency and a 72% protein feed conversion efficiency. These efficiencies are lower than those of plant-based and insect-based meat alternatives but remain higher than those associated with conventional animal-based meat (Alexander *et al.*, 2015).

Table 6: Life cycle assessment (LCA) of alternative proteins (Hadi and Brightwell, 2021)

Category	**Energy use (MJ/kg)**	**GHG Emission ($kgCO^{2-}eq/kg$ Product)**	**Water Use or Eutrophication**	**Land Use (m^2a/kg)**	**Reference**
Cultured meat					
Minced beef	26-33	1.90-2.24	0.36–0.52 m^3/kg meat (W)	0.19–0.23	Tuomisto and Mattos, 2011
CHO	106	7.5	7.9 gPO^{4-}eq/kg meat (E)	5.5	Mattick *et al.*, 2015
Plant-based meat					
Beyond Burger®	54.15	3.35	28.84 m^3/kg meat(W)	3.97	Heller and Keoleian, 2017
Impossible Burger®	NA	3.5	0.11 m^3/kg meat(W); 1.3 gPO^{4-}eq/kg meat	2.5	Khan *et al.*, 2019
Insect protein					
Mealworm (T. molitor and *Zophobas morio*)	33.68	2.65	NA	3.56	Oonincx and de Boer, 2012
Black soldier fly (*H. illucens*)	21.20–99.60	1.36–15.10	NA	0.032–7.03	Smetana *et al.*, 2016
Cricket (*G. bimaculatans* and *A. domesticus*)	NA	2.29	0.43 m^3/kg cricket(W); 0.00047 kgP-eq and 0.020 kgN-eq/kg cricket(E)	NA	Halloran *et al.*, 2017
Single-cell protein					
Spirulina tablets (*A. platensis*)	7.88-12.7	5.05-7.71	0.015–0.022 kgN-eq/kg tablet(E)	NA	Ye *et al.*, 2018
Mico algal protein (*A. platensis*)	1225.6-338.3	78.1-96.3	3.2–3.3 m^3/kg protein meal(W); 49.2–85.3 kgN-eq/kg protein meal(E)	1.7-4.3	Smetana *et al.*, 2017
Micro algal protein (*C. vulgaris*)	217.1-4181.3	14.7-245.1	0.3–3.9 m^3/kg protein meal(W); 40.6–105.3 kgN-eq/kg protein meal(E)	1.9-5.4	Smetana *et al.*, 2017
Mycoprotein	60.07-76.8	555-6.15	NA	0.79-0.84	Smetana *et al.*, 2015
Bacterial protein (*Cupriavidus necator*)	NA	0.81-1	0.0001–0.0038 m^3/kg protein (W); 0.000333 kgP-eq/kg protein (E) 2.5 m^3/kg protein(W)	0.029-0.085	Sillman *et al.*, 2020
Bacterial protein (hydrogen-oxidizing bacteria)	200	8	0.0025 kgP-eq/kg protein and 0.00035N-eq/kg protein (E)	0.8	Järviö *et al.*, 2021

Water use (W) is expressed in volumetric unit (m^3or L/weight of product), whereas eutrophication (E) is a measure of the number of contaminants released into freshwater or marine environments (g contaminant/weight of product). Land use is expressed in annual area occupation (m^2a). LCA was conducted based on the proliferation of Chinese hamster ovary (CHO) in a growth medium mainly comprising basal medium and soy hydrolysate

Nutrition

Plant-derived proteins commonly used in plant-based meat (PBM) products such as pea, soy and wheat which can deliver overall protein levels comparable to those of animal meat. However, achieving a well-balanced amino acid profile typically requires blending different plant protein sources. For example, legume proteins are rich in lysine but limited in sulphur-containing amino acids, whereas cereal proteins show the opposite pattern. Combining these two groups therefore provides a more complete and nutritionally balanced amino acid composition (Neacsu *et al.*, 2015) Nutritional characteristics also differ between traditional and modern plant-based meat (PBM) products. For instance, both tofu, a traditional PBM and Impossible™, a newer PBM product, provide advantages over animal-based meats, including the presence of dietary fibre and essential minerals, along with the absence of cholesterol. Yet, each product offers distinct benefits like tofu is lower in calories, contains less fat and is naturally free of sodium, whereas Impossible™ products typically offer higher protein levels and are fortified with vitamin B12 (Hu *et al.*, 2015).

Different cultured cell types supply distinct nutritional components differentiated muscle cells are expected to provide most of the protein, while mature adipocytes contribute to the overall fatty acid composition. However, some nutrients naturally present in animal-based meat (ABM) are absent from cultured cells. For instance, vitamin B12 is produced exclusively by bacteria and therefore must be added externally. Similar to claims about flavour enhancements, advocates of cultured meat (CBM) argue that its nutritional profile can match or even surpass that of ABM, with the possibility of tailoring nutrient content through co-culture systems, media enrichment, or genetic engineering **(**Datar and Betti, 2010). The composition of the culture media plays a critical role in determining cell viability and growth efficiency, and also influences the nutritional characteristics of the final product potentially even affecting its flavour and taste. More complete nutritional data for cultured meat (CBM) are expected to emerge as early commercial products enter the market, production scales up, and scientific research in this area continues to expand (Rubio *et al.*, 2020).

Table 7: Differences in nutritional composition in ready-to-use meat alternatives and meat (products).

Category	Energy (Kcal/100g)	Protein (g/100g)	Total Fat (g/100g)	Saturated Fat (g/100g)	Fibre (g/100g)	Salt (g/100g)	references
Plant based sausages	254	17.0	15.0	1.90	3.00	1.50	Rizzolo-Brime *et al.*, 2023
Plant based nuggets and breaded food	229	12.3	10.2	1.20	3.80	1.23	Rizzolo-Brime *et al.*, 2023
Plant-based meatballs	189	16.0	9.60	1.10	5.20	1.42	Rizzolo-Brime *et al.*, 2023
Veggie patties	202	14.0	9.50	1.20	3.85	1.19	Rizzolo-Brime *et al.*, 2023
“Beyond Meat-type” hamburger patties	201	15.5	9.25	1.25	4.00	135	Rizzolo-Brime *et al.*, 2023
“Chicken type” strips	154	19.0	5.30	0.55	6.40	1.40	Rizzolo-Brime *et al.*, 2023
Plant based minced	320	47.30	8.80	1.50	6.00	1.40	Rizzolo-Brime *et al.*, 2023
Vegan burger	196	13.15	9.17	1.6	4.45	0.41	Romão *et al.*, 2022
Seafood	101	24	14	9	0	0.111	Romão *et al.*, 2022
Beef	183	67.8	11.0	4.37	0	0.059	Drewnowski *et al.*, 2022
Pork	166	70.1	9.01	3.00	0	0.079	Drewnowski *et al.*, 2022
chicken	171	18.9	10.0	2.77	0	0.082	Drewnowski *et al.*, 2022

The Soil–Plant–Environment Continuum of Meat Alternatives

Sustainable production of meat alternatives must be understood within a soil–plant–environment continuum, as both the environmental footprint and nutritional quality of alternative proteins ultimately originate from soil-based agricultural systems (Lal, 2020). Plant-based meat alternatives rely primarily on crops such as soybean, pea, wheat, faba bean and other legumes and cereals, whose yield, protein concentration and micronutrient composition are strongly governed by soil health, nutrient availability, and soil biological activity (Kopittke *et al.*, 2019). Key soil properties, including soil organic carbon content, nitrogen and phosphorus cycling, microbial diversity and soil water-holding capacity, play a critical role in regulating crop productivity and protein quality, thereby influencing the efficiency and sustainability of downstream processing into meat analogues (Kopittke *et al.*, 2019). When soils are degraded, greater inputs of synthetic fertilizers and irrigation are often required, leading to increased greenhouse gas emissions, higher eutrophication potential and elevated energy demand, factors that can undermine the environmental benefits commonly attributed to plant-based and hybrid meat alternatives (Poore and Nemecek, 2018). In contrast, healthy and well-managed soils enhance nutrient-use efficiency, support carbon sequestration and reduce reliance on external inputs, thereby improving the overall sustainability performance of alternative protein supply chains (Lal, 2020). Therefore, integrating soil health into life cycle assessment (LCA) and sustainability evaluations of meat alternatives is essential for accurately assessing their true environmental benefits and for advancing resilient and sustainable food systems (Poore and Nemecek, 2018).

Future Outlook

Future developments in alternative protein technologies will be driven by advances in material science, cell biology, bioprocess engineering and microbial biotechnology. Plant-based meat (PBM) research is expected to focus on improving protein functionality, fibre alignment and flavour precursor generation, while reducing reliance on highly processed ingredients. Emerging platforms such as mycoprotein and precision-fermented proteins may contribute to more structurally and nutritionally sophisticated formulations. In parallel, cell-based meat (CBM) will require significant scientific progress to overcome persistent challenges in scalable bioreactor design, serum-free media optimisation, and long-term cell line stability. The absence of comprehensive datasets on CBM's nutritional, sensory, and techno-economic performance remains a critical research gap and future validation will depend on rigorous pilot-scale and industrial-scale studies. Hybrid PBM–CBM systems particularly through incorporation of cultured adipocytes to enhance flavour and juiciness which represent a near-term research priority with strong potential for cost reduction. Overall, the integration of multi-disciplinary scientific approaches and standardized evaluation frameworks will be essential for establishing reliable, safe, and nutritionally competitive meat alternatives at commercial scale.

Conclusion

Meat alternatives have emerged as a critical component of future food systems, driven by the need to address escalating environmental pressures, public health risks, and ethical concerns associated with conventional livestock production. Plant-based meat technologies have already achieved substantial advances in protein structuring and sensory performance, supported by innovations in extrusion, spinning, shear processing, and 3D printing. Cultured meat holds the greatest potential to replicate the cellular and nutritional profile of animal tissue; however, it faces substantial barriers related to cost, scalable bioprocess design, and limited empirical data on environmental and nutritional outcomes. Microbial, fungal, algal, and insect proteins offer additional high-efficiency, low-resource solutions but require further optimization in flavour, safety, and consumer acceptance.

The long-term success of next-generation meat alternatives will rely on integrating advances in protein chemistry, cell biology, bioreactor engineering and precision fermentation with robust regulatory frameworks and standardized sustainability assessments. Hybrid PBM–CBM systems represent a practical intermediate step, offering improved sensory attributes at reduced cost. Ultimately, diversified alternative protein strategies, rather than a single dominant technology will be essential to building a resilient, sustainable and ethically responsible global protein supply.

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