Chapter 1
Meat Analogs: Prospects and Challenges

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1.1 Introduction

Meat has been an integral part of the human diet since time immemorial and has played an important role in fulfilling the nutritional requirement for growth and development in addition to social and cultural roles. Meat is an excellent source of animal proteins having higher bioavailability and digestibility, essential amino acids, lipids, minerals, vitamins, and bioactive peptides. Compared to plant proteins, meat proteins have higher nutritive value due to the presence of essential

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amino acids and higher digestibility of these proteins in human digestive tracts (Kaur et al. 2022; Kumar et al. 2022a).

The meat production system is basically an inefficient conversion of vegetable proteins into meat proteins by rearing animals, followed by their slaughter. Thus, compared to production of plant proteins, meat production requires higher inputs and has high carbon, water, and land footprints (Kumar et al. 2017). In addition to this, the issue of animal welfare due to the involvement of animals in meat production, food safety risks (antibiotic resistance, food borne-diseases, illness, metabolic diseases), risk of zoonotic diseases (due to agriculture intensification, meat packaging plants, etc.), also pose significant challenges in the meat production. Meat and meat products also need to have an efficient cold chain facility in place to prevent their spoilage and to extend the shelf life (Kumar et al. 2020a, b). In addition to animal welfare issues (during intensive rearing, slaughtering, and habitat destruction), consumption of meat and meat products, mainly red and processed meat products, has been associated with an increasing risk of cardiovascular diseases, hypertension, and colorectal cancers (Bouvard et al. 2015). Thus, it is widely recommended to reduce meat consumption to improve the health of humans and the environment (Kumar et al. 2022b).

The world's population has recorded rapid growth in the last century, especially in Asia and Africa, and touched the 8 billion marks on 15th Nov 2022 (United Nations 2022). It is expected to reach 9.8 billion in the year 2050 and 11.32 billion in the year 2100. A 60% higher agriculture production and 76% more meat production will be required to meet the food requirement for the population in the year 2050 as compared to agriculture and meat production levels in the year 2005–2006 (Alexandratos and Bruinsma 2012). Further, in the last five decades, a four-fold growth in food consumption was observed with a two-fold increase in the population, thus, on average, twice the increase in food consumption (Weis 2015). Ensuring proper food availability and food safety for this rapidly increasing population will be an upheaval task, considering that all the natural resources are under severely strained conditions and have already been used to their full potential; thus, this sector needs to be shifted from a more sustainable production system.

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As per one estimate, about 83% of total farmland is used for animal production activities, contributing to 56–58% of total emissions but only 37% of total protein supply and 18% of total energy supply (Poore and Nemecek 2018). The environmental footprint of vegetable proteins is markedly lower than those of meat proteins as vegetable proteins have 2–6 g CO_2e/kg protein carbon footprint, 38–205 blue water footprint, and 6–8 m^2 year/kg protein land use footprint as compared to their corresponding values for the beef production viz., 174–184, 1607 and 1310–1311, respectively (Thrane et al. 2017). Bluewater refers to the total surface water and groundwater. Bluewater footprints indicate the volume of freshwater evaporated from the global blue water resources, viz., groundwater, lakes, reservoirs, ponds, glaciers and rivers (Mehta et al. 2021).

With the advancement of processing technologies, plants and other non-meat proteins can be processed into meat analogs by imitating the meat products in their structure, chemical nature, and sensory attributes (Kumar et al. 2022c). These plant-based meat analogs provide sustainable and healthy alternatives to meat and have noticed increasing acceptance among consumers who prefer a sustainable and healthy diet (Kaur et al. 2022). Similarly, the EAT-Lancet Commission also recommended reducing meat and dairy consumption and increasing plant-based diets comprising more legumes, beans, and nuts (Willett et al. 2019). Thus, meat analogs could play a vital role in ensuring the sustainability of global food security (Fig. 1.1).

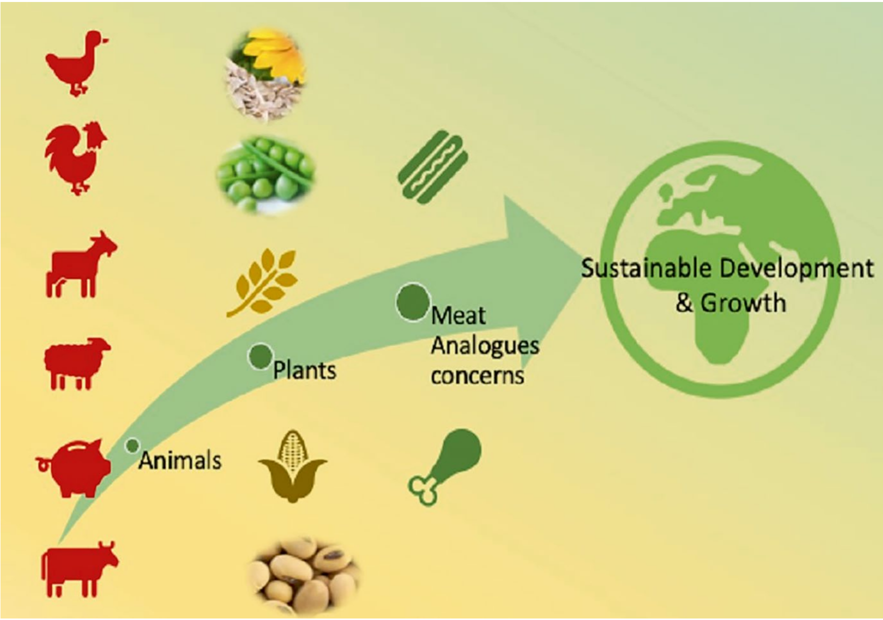

Fig. 1.1 Role of plant-based meat analogs in sustainable development and growth

1.2 Current Status

The global meat analog market has grown tremendously over the last two decades. According to a Bloomberg Intelligence report on the plant-based food market, the market size of plant-based meat analogs is expected to touch 74 billion USD in 2030 from 4.2 billion USD in 2020 (Bloomberg Intelligence 2021). The report attributed the higher growth in this sector to the increasing awareness among consumers towards health consciousness, sustainability merits, increasing availability, and price advantages of plant-based meat analogs. Further, if the current trends continue, the sale of plant-based meat analogs could reach 118 billion USD in 2030 (Bloomberg Intelligence 2021). In 2023, the total sale of meat alternatives was projected to touch 10.15 billion USD by following a CAGR (compound annual growth rate 2022–2028) of 10.58%, with China ranked first in the total growth (Statista 2023). Globally, Europe has the largest market for plant-based meat analogs with 51.5% of the market share, followed by 26.8% share of North America, 11.8% share of Asia Pacific, 6.3% share of Latin America and 3.6% share of Middle East and Africa (OECD 2021).

The main drivers for this growth are increasing numbers of start-ups and food processing companies that make the availability of meat analogs at lower prices, higher diversity, and varied tastes as per local preferences, advanced packaging, improving the nutritive value and functionality of plant proteins, application of a more sustainable, cheaply available, and unconventional source of plant and insect proteins in the preparation of meat analogs (Sharma et al. 2022).

The plant-based meat analog sector has seen tremendous growth in the USA with the increasing targeting of flexitarian and vegetarian consumers by meat alternative companies (Choudhury et al. 2020). The USA market for plant-based meat analogs was 939 million USD in 2019, which accounted for 2% of all sales of packaged retail meat and 1% of all retail meat. Further, during the 2018–2019 year, the total sale of plant-based meat analogs was recorded as the third fastest growing sector among plant-based foods by recording 19% sales and touching 1.4 billion USD (Good Food Institute 2023). In the USA, the market share of plant-based meat analogs was projected to reach 15.7 billion USD in 2027 and 27.9 billion USD by 2050 (Marketsandmarkets 2023). Soy-based meat analogs have the largest market share and have seen high growth in European and North American countries. Among types of meat analogs, plant-based beef analog dominates the market, with burger patties projected to record the highest growth rate by 2027 (Marketsandmarkets 2023). Furthermore, the largest market share for plant-based meat analogs in 2020 was in Europe, and it is projected to maintain the lead in the future due to the increasing awareness among consumers for healthy, natural diets and the increasing trend of vegetarianism (Marketsandmarkets 2023).

Table 1.1 presents various ingredients used in the commonly available plant-based meat analogs.

Table 1.1 Ingredient list of some commonly available plant-based meat analogs

Analog product	Manufacturer	Main ingredients			
		Protein	Lipid	Carbohydrate	Additives
Beyond burger	Beyond Foods, USA	Pea protein isolates, rice protein, mung protein	Canola oil, sunflower oil, coconut oil	Potato starch, methylcellulose,	Apple extract, beet juice, vinegar, lecithin, salt, pomegranate fruit powder
Impossible burger	Impossible Foods, USA	SPC, SPI, potato protein	Coconut oil, sunflower oil	Modified starch, methylcellulose, cultured dextrose	Soy leghemoglobin, salt, yeast extract, zinc, vitamins B_1, E, C, B_2, and B_{12}
MorningStar farms grillers burger	MorningStar Farms, Kellogg's, USA	Wheat gluten, soy flour, SPI, egg whites	Corn oil, sunflower oil, canola oil	Corn starch, potato starch, xanthan gum, sugar, gum acacia, methylcellulose	Salt, yeast extract, onion powder, soy sauce, carrot juice, garlic powder, whey, tomato paste, onion juice, calcium caseinate
Boca all American veggie burger	Boca Food Company, Kraft Foods, USA	SPC, wheat gluten, SPI, cheese powder, low-fat cheddar cheese	Corn oil, sesame oil	Methylcellulose	Additives: spice, salt, herbs, dried garlic, HSP, mannitol, yeast extract
Gardein meatless meat ball	Garden Protein International, Pinnacle Foods, Canada	SPC, wheat gluten, SPI, barley malt extract, pea protein	Canola oil	Wheat flour, sugar, cane sugar	Salt, yeast extract, sea salt, spice, dried garlic, dried onion, vinegar, vitamin B_2, B_5, B_1, folic acid
Tofurky ham roast with glaze	Tofurky, Turtle Island Foods, USA	Wheat gluten, tofu,	Canola oil	Oat fiber, cane sugar, konjac fiber, carrageenan, xanthan gum, dextrose	Spice, lycopene, carrot juice, salt, garlic, KCl
Quorn brand chik'n nuggets	Quorn Foods, Inc., UK	Mycoprotein, egg white, wheat gluten, whole egg	Canola oil	Wheat flour, sugar, cane sugar, turbinado sugar, dextrose, pea fiber	Yeast extract, salt, calcium acetate, black pepper, yeast, onion powder, calcium chloride

Adapted and modified from Bohrer (2017)

SPC soy protein concentrate, *SPI* soy protein isolates, *HSP* hydrolyzed soy protein, *KCl* potassium chloride

1.3 Major Ingredients

In the development of meat analogs, protein, lipids, and moisture form the major components, followed by carbohydrates, minerals, vitamins, and other food additives (colorants, flavorings, taste enhancers, etc.). In plant-based meat analogs, plant protein is the important component that affects the product's texture, appearance, and nutritional quality. The meat analogs with the desirable nutritive and sensory attributes could be prepared with a suitable selection of ingredients and processing methods. Plant-based meat analogs contain about 50–80% moisture, 4–25% protein, 2–30% carbohydrate, 0–15% lipids, and 0–15% additives comprising seasonings, salt, spices, pigments, colorants, flavorings, and binding agents (Chen et al. 2022; Huang et al. 2022). Protein plays an important role in nutritive value and structural attributes. Carbohydrates make cross-linking with proteins and act as fillers, binders, and thickeners (Chen et al. 2021; Huang et al. 2022). The incorporation of lipids improves nutritive quality, sensory attributes, and storage stability of meat analogs (McClements and Grossmann 2021).

1.3.1 Plant Protein Sources

Vegetable proteins, due to their high nutritive value and relatively cheap availability, are commonly used in the development of canned meat analogs and pet foods (Featherstone 2015). Soybean and wheat gluten remain the primary source of vegetable proteins in the development of plant-based meat analogs in addition to groundnut, zein, cereal proteins, pulses/legumes, nuts, fungi, and yeast, also commonly used in the preparation of meat analogs (Kumar et al. 2022c; Sharma et al. 2022).

The easy availability, low cost, high nutritive value, and textural attributes make soy protein the most popular and common ingredient in developing plant-based meat analogs (Krintiras et al. 2015; Kumar et al. 2023). Soy in different forms, such as soy flour, spray-dried soy milk, texturized soy protein (TSP), soy protein concentrate (SPC), and soy protein isolates (SPI), are commonly used due to their nutritional, functional attributes (texturizer, emulsifier, stabilizers, water holding capacity), satiating properties, sensory attributes, wide availability, and inexpensive/ low cost (Kumar et al. 2022c). The biological value of SPI is reported to be comparable to meat, with both having equivalent PDCAAS (protein digested corrected amino acid score) of 1.0 (Kumar et al. 2023). In addition, the intake of soy-based meat analogs leads to a long-lasting satiating effect and causes lower food intake after consuming these products (Williamson et al. 2006).

The legumes (peas, lupin, lentils, chickpea, and mung bean) have better amino acid profiles than cereals and have lysine, leucine, and phenylalanine content equivalent to soy protein. Legume seeds have high protein content (ranging from 20–35%), dietary fiber, saturated fat, vitamins, and minerals; hence their inclusion in meat analogs results in improving the nutritive quality of meat analogs (Doss et al. 2022). The digestibility of legume protein is lower as compared to soy protein; however, by suitable processing technologies, legumes are increasingly used in the development of functional meat analogs such as improved textural and fibrousness, gluten-free, lower allergen ingredients and organoleptic attributes (Vatansever et al. 2020).

Wheat gluten is the most commonly used traditional cereal protein in the development of meat analogs. The visco-elastic properties of wheat gluten form the fibrous texture and impart strength to the product, thereby improving binding, solubility, baking properties, swelling, and leavening properties (Kumar et al. 2012). However, it should be noted that cereals are a rich source of carbohydrates, and their digestibility and protein content are lower than those of soy (Joshi and Kumar 2015; Mota et al. 2016). Thus, it needs to be compensated with other suitable ingredients to get the desired nutritional profile of the meat analogs. In addition, wheat gluten is a rich source of glutamine amino acid but deficient in threonine and lysine amino acids. Although used in meat analogs, zein protein available in maize is not widespread due to its inability to form fiber structure or sheet-like texture at ambient temperature (Jeong et al. 2017). It can be successfully incorporated into meat analog preparations with suitable technological interventions such as hydrolysis, crosslinking, deamination, or mixing with other protein sources (Glusac and Fishman 2021).

Rice protein is used in the preparation of gluten-free meat analogs for people with gluten intolerance or celiac disease. The incorporation of rice bran in meat analogs improves the nutritive and functional quality due to its high dietary fiber content (27.6–33.3%) (Xiao et al. 2022). The rice protein does not have a strong flavor like soy protein in addition, it has a hypoallergic and hypocholesterolemic effect (Detchewa et al. 2022). Further, the nutritive value of rice protein in terms of digestibility and biological values are similar to SPI (Han et al. 2015), thus a suitable nutrition source for infants and elderly persons (Jeong et al. 2017). Rice protein has methionine, arginine, valine, histidine, and cysteine amino acids in high concentrations, and its lysine content (3.8%) and leucine content (8.2%) are higher than wheat protein (Kumar Singh et al. 2016).

Further with the advancement in processing, extraction and purification of plant proteins, various other non-conventional sources of plant proteins such as algae, fungi, single-cell-protein (SCP)/microbial proteins/edible unicellular micrograms, leafy vegetables, agriculture byproducts, seaweeds, oilseeds proteins, jackfruits, pseudocereals (such as Quinoa and Amaranthus, etc.) are gaining popularity due to their sustainability potential and nutritive value (high protein content, presence of essential amino acids) and price advantage in the meat analogs (Delshadi et al. 2020; Kurek et al. 2022; Yesuraj et al. 2022). Quinoa seed protein has excellent binding, moisture retention, emulsifying, and foaming properties equivalent to soy proteins. Further, soy quinoa seed protein has good gelling properties at low pH (Kaspchak et al. 2017).

The proteins obtained from potato, chia seed, hemp, and pumpkin seeds have good solubility in alkaline medium and other function attributes such as gelling, foaming, and moisture retention. They could be harvested for their potential use in the formulation of meat analogs (López et al. 2018). Konjac fiber obtained from konjac plant root is gaining popularity as an ingredient in meat analogs due to associated health benefits. In addition, the application of konjac fiber in Tempeh (a fermented soy product) was observed to improve functional attributes such as viscoelasticity, fibrousness, increased water retention, and overall texture of the products (Yuliarti et al. 2023). Further, protein harvested from leaves from grass, tobacco, alfalfa, sugarcane, etc., could also be utilized as a cheaper source of proteins in meat analogs (Singh et al. 2021).

Mycoprotein (protein obtained from fungi) has a comparatively lower environmental impact as it requires 10–20 times less land and has a ten times lower carbon footprint as compared to beef production, whereas four times lower carbon footprint as compared to poultry (Hashempour-Baltork et al. 2020). These are rich sources of nutrients and have a good quantity of essential amino acids, minerals, carotene, and vitamins. The mycoprotein from *Fusarium graminearum* (a filamentous edible fungi) has a nutritive quality similar to that of meat, such as meaty flavor and taste, fibers, fibrous texture, and high digestibility. On average, mycoprotein contains 45% protein and 25% fiber, mainly contains 75% β-glucan and chitin, 13% fat, and 10% carbohydrates (Finnigan et al. 2019). Mycoprotein forms the fibrous chitin-glucan matrix and is recognized as 'high in fiber food' by the European Union (Commission 2020).

Mushroom incorporation in the meat analogs imparts a specific flavor, light grey color, and nutritive value. The texture and binding of such products (mushroom-based) could be further improved by adding various gelling thickening agents and binding, such as carrageenan and xanthan gum. A good quality plant-based meat analog was developed by adding mushrooms in texturized soy protein, wheat gluten, egg albumen, and food additives (Kumar et al. 2011, 2012).

1.3.2 Carbohydrate Sources

During the preparation of meat analogs, carbohydrates are incorporated to modify texture, structure, and consistency (Yao et al. 2004). The primary sources of carbohydrates in meat analogs are either as binders/fillers such as starches from corn, potato, rice, wheat, peas, and cassava or in minor quantities of gums, methylcellulose, and carrageenan. In meat analogs, carbohydrates play an important role in imparting functional properties such as gelation, reducing power, gelling, dehydration, and degradation (Huang et al. 2022). Carbohydrates in their native or refined form are classified as food additives and used in food to improve taste, appearance, and mouthfeel (Huang et al. 2022). As such, meat contains very low levels of carbohydrates; thus, while preparing analogs for fresh meat cuts, the carbohydrate content is kept very low, similar to their meat counterparts, and has a role in the Maillard reaction affecting color and flavor similar to fresh meat cuts (Sohail et al. 2022).

However, in the development of analogs for processed meat products, the level of carbohydrates could be high to maintain the structural and textural properties.

The starch in water forms a gel-like structure, which gives smoothness and fat-like properties, thus used to prepare low-fat meat analogs (Joshi and Kumar 2015). The application of sugar balances the hardening effect of salt and improves the flavor and taste of the product. To get the maximum health benefits from carbohydrates, they should be utilized in minimally processed form as refined or processed carbohydrates could alter their nutritive value, especially by decreasing the fiber content (Viuda-Martos et al. 2010). Methylcellulose, a dietary fiber obtained from cellulose, is used as a binder in the development of meat analogs (Schuh et al. 2013).

1.3.3 Lipid Source

Lipid forms an essential component of the meat analog as it affects the sensory, textural, and nutritive quality of the meat analogs. Fat improves the mouthfeel, juiciness, appearance, tenderness, and flavor of the product by interacting with the other macronutrients in food products (Chen et al. 2023a, b). There is a significant difference in the structure and composition of lipids derived from animal and protein sources, such as isomerization, degree of unsaturation, physical state (solid state of animal fat vs liquid state of vegetable oil), fatty acid profiles, and physicochemical properties. These differences cause variations in the sensorial attributes of the meat analogs, such as mouthfeel, aroma, spreadability, juiciness, and texture (McClements and Grossmann 2021).

Thus, proper selection of lipids is required during the preparation of meat analogs by carefully considering various factors such as sensory attributes, nutritive value, functionality, cost, availability, chemical stability, and traditions/ customs (Chen et al. 2023a, b). Based on the origin, the lipids used in the meat analog manufacturing can be divided into two categories viz., (i) exogenous lipid source obtained from oilseeds and tropical sources such as coconut oil, canola oil, sunflower oil, flaxseed oil, and soybean oil; and (ii) endogenous lipid already present in the less-refined or partially fractionated protein ingredients (Bohrer 2019). Further, with increasing focus on healthier food and sustainable food production, the lipids obtained from nuts, fruit seeds, fruit peels, grain embryos, and agro-byproducts are increasingly used to prepare meat analogs (Chen et al. 2023a, b).

At present, the primary sources of lipids in plant-based meat analogs are canola oil, sunflower oil, palm oil, coconut oil, sesame oil, cocoa butter, and corn oil (Bohrer 2019). The lipid content of commonly available meat analogs is equivalent to the meat products. Furthermore, vegetable oils are considered a healthier option due to the absence of cholesterol (Dekkers et al. 2018; Pietsch et al. 2017, 2019). Oleogels (having properties of solid fat with >90% fat w/w, reduced amount of trans and saturated fat) are used to replace detrimental fat in food products (Manzoor et al. 2022). These oleogels are nowadays used as replacements for fat in meat analogs (Martins et al. 2019). Various fat replacers also used in meat analogs, such as oat soluble fiber in low-fat meat analogs, improve the water-binding properties and structural attributes (Piñero et al. 2008; Summo et al. 2020).

1.3.4 Miscellaneous Ingredients

In addition to protein, fat, and carbohydrates, meat analogs and other ingredients play a major role in affecting sensory attributes and the nutritive quality of meat analogs. Flavor is an important parameter that determines the consumer acceptance and marketability of food products. Meat is a rich source of zinc, vitamin B_1, B_{12}, B_3, B_6, and sodium ascorbate, and to improve the nutritive value similar to meat, these compounds are added during the development of meat analogs (Damayanti et al. 2018).

1.3.4.1 Flavorings

Developing the meat-like flavor in plant-based meat analogs remains a challenge as the flavor of the meat is formed by a complex mechanism involving more than 1000 compounds (Wang et al. 2018). The free amino acids, short peptides, inorganic salts, and metabolic products of nucleic acids such as ribose inosine play important roles in the flavor development of meat. Furthermore, the aroma developed from volatile compounds during heating, such as sulfur-containing compounds, ketones, aldehydes, and heterocyclic compounds, also have major role in the flavor development of meat (Robbins et al. 2003). The flavor of meat products is the result of very complex mechanisms involving several products by Maillard reaction, oxidation of lipids, and thiamine degradation (Robbins et al. 2003). The vegetable protein most commonly used in the preparation of plant-based meat analogs does not have these critical compounds needed for flavor development.

Soy has a beany, grassy, astringent, and chalky odor, which gives an undesirable off-flavor to soy protein-based meat analogs (Damodaran and Arora 2013; Zhu and Damodaran 2018). The origin of this off-flavor is credited to the oxidation of unsaturated fatty acids by lipoxygenase enzyme released due to breaking cell wall (Kumari et al. 2016), consequently leading to the formation of non-volatile substances such as esters and long-chain alcohols (Zhu and Damodaran 2018). The lipid forms up to 20–33% of raw soybean, and it contains mainly monounsaturated fatty acids (as oleic acid) and polyunsaturated fatty acids (as linoleic and linolenic acid) (Damodaran and Arora 2013). This problem of off-flavor by soy protein usage in meat analogs could be alleviated using various processing methods such as enzymatic decomposition, acid treatment, genetic engineering, and solvent extraction (Li and Li 2020).

To get a flavor similar to meat, various flavorings/flavor enhancers are added to meat analogs, such as aromatic plants or herbs, spices, hydrolyzed vegetable proteins, yeast extracts, vegetable oils, seasonings, etc. Hydrolyzed vegetable protein

(HVP) imparts flavor to meat analogs in addition to increasing the protein content of the meat analogs (Aaslyng et al. 1998; Kumar et al. 2017). HVPs are prepared by enzymatic hydrolysis under mild acidic and temperature conditions of plant proteins such as wheat, soy, corn, mushroom, etc., into short peptides and free amino acids. HVP contains several volatile compounds such as furans, pyridines, furanones, organic acids, pyrrole, pyrazines, alcohols, aldehydes, esters, ketones, sulfur-containing compounds, and phenols (Aaslyng et al. 1998). These compounds produce a meat-like flavor upon heating with reducing sugars and yeast autolysis (Aaslyng et al. 1998). Similarly, the hydrolysis of rapeseed protein with trypsin and neutral protease obtained from *Bacillus subtilis* was observed to facilitate Maillard's reaction and meat-like favor (Kale et al. 2022).

Yeast extract (YE) prepared from food-grade yeast (brewer's yeast and baker's yeast) is a rich source of protein, volatile compounds, reducing sugars, amino acids, peptides, thiamine, lipids, peptides, and nucleic acid content (Aaslyng et al. 1998). The volatile flavor compounds such as thiophene and pyrazine impart a sweet and meaty aroma to roasted products (Lin et al. 2014). Spice and herbs have their typical flavor and aroma and are used to prepare food products to develop aroma, flavor, and taste. Due to their essential oils and phenolic compounds, these exert antioxidant and antimicrobial effects, leading to improving shelf life and masking undesirable flavors (Awad et al. 2021, 2022). Allicin present in garlic degrades to alkyl sulfides, leading to the development of a meat-like flavor (Lanzotti 2006).

1.3.4.2 Colorants

The appearance and color of meat analogs should match the color and appearance of their meat counterparts to increase consumer acceptance. Further, it is also desirable to have raw and cooked meat analogs whose color and appearance are similar to that of meat products (Mancini and Hunt 2005). Color is an intrinsic attribute of the food product that consumers notice and affects the consumer perception of taste and overall acceptability of a food product. Altering the hue and chroma, along with the taste of a food product, was observed to have a dramatic effect on consumer expectations and experience (Spence 2015).

Meat color is mainly affected by the oxidative state of myoglobin and, to some extent, other components such as lipids, protein status, etc. The bright red color of fresh red meat is attributed to oxymyoglobin (bloom). In contrast, the brown color of cooked meat is attributed to metmyoglobin formation during cooking (Suman and Joseph 2013). The color of raw plant-based meat analogs is yellow or beige due to various pigments, and it has been a challenge to mimic the typical brown color of cooked red meat by applying suitable colorants (Sakai et al. 2022). To imitate the meat-like color of plant-based meat analogs, the industry commonly uses beet red pigment and soy leghemoglobin (Bohrer 2019).

The beet red pigment consists of betanidin/betanin pigment extracted from the beet plant (*Beta vulagaris*). It has a high margin of safety and a low production cost; thus, it is widely used in food products to impart red color (Strack et al. 2003). In addition to imparting color, betanin has a high antioxidant effect, thus positively affecting consumers' health by protecting cells against oxidative stress (Fernández-López et al. 2020; Vulić et al. 2013). However, unlike myoglobin, betanin is thermostable and photostable, thus maintaining its natural red color even after cooking and overheating, it gives a yellow color, which has poor consumer acceptance (Bohrer 2019; Sakai et al. 2022; Strack et al. 2003).

Leghemoglobin is a genetically modified protein expressed in *Pichia pastoris* yeast. It resembles myoglobin chemically and structurally and imparts a brown color to cooked meat analogs similar to the meat (Goldstein et al. 2017). Although it is safe to consume, some consumers still have concerns about its consumption. In addition to developing the desired level of Maillard reaction (browning) for color and flavor development, various precursors such as caramel color, reducing sugars, malt extracts, and amino acids are added to mask the red color and impart the brown color of cooked meat analog (Dennis et al. 2015).

To stabilize the color of meat analogs during cooking, various ingredients such as citrus fruit extract, ascorbic acid, and apple extract are added in combination with natural color pigments such as lycopene, and annatto (Mattice and Marangoni 2020). Apple extracts for color and citrus fibers to provide a meat-like texture were used by Herbafood Inc. to produce vegan burger patties. In addition to the color, the application of extract also improved the antioxidant potential of the meat analogs. Beet juice is used in Beyond Burgers and tomato paste by MorningStar to get the desired color of the meat analogs (Fraser et al. 2018). Recently, the application of freshwater unicellular green algae *Haematococcus Pluvialis* was used for imparting color as well as improving oxidative stability to the meat analogs due to its high content of carotenoids as 69.7% astaxanthin, 3% beta-carotene, and 27% lutein (Huang et al. 2023). Further, the incorporation of astaxanthin was observed to provide a meat-like color to meat analogs (Fu et al. 2021). Similarly, application of natural pigments viz., oleoresin paprika, red beet (0.4–1.5 mg/g), sorghum, cacao pigment (1.1–1.3 mg/g), and monascus red, were used to develop color to a plant-based meat analog product similar to cooked meat color (Ryu et al. 2023).

Table 1.2 Summarize the ingredients used and their role in the development of plant-based meat.

1.4 Processing of Plant Protein

Plant proteins are processed using various technologies such as extrusion, spinning, and cross-linking to impart fibrous texture. The functional attributes of plant proteins, such as gelling ability, solubility, water binding ability, viscosity, gelation, flavor, texturization, dough bindings, etc., are affected by composition (amino acid content) and processing conditions. These functional attributes play a crucial role in imparting meat-like properties to meat analogs, and these could be modified by using suitable processing such as denaturation induced by heat, alkali or acid treatment, extraction methodology, enzymatic action, and hydrolysis. The enzymatic

Table 1.2 Various ingredients in plant-based meat analog and their role

Ingredients	Amount (range)	Sources	Role
Moisture	40–75%	Potable water	Carrier medium for other ingredients, plasticizers, juiciness, texture, palatability
Protein	3–28%	Conventional: Soy, wheat gluten, rice, zein, peas, pulses, legumes Unconventional: leafy protein, grass, potato, oilseed proteins, algal, mycoprotein, SCP	Texture, structure, functional attributes, nutritive value
Carbohydrates	1–30%	Starch and sugar from Major components: corn, potato, rice, wheat, peas, cassava Minor components: gums, methylcellulose, carrageenan	Filler, binder, gelling, hydration, dehydration, flavor, color by Maillard reaction, taste,
Lipids	2–30%	Exogenous: soybean oil, sunflower oil, cocoa, flaxseed Endogenous: less refined or partially fractionated legume proteins, maize, cereals	Flavor, mouthfeel, juiciness, tenderness, nutritive value, texture
Additives	0–12%	Salt: sodium chloride	Taste, flavor, preservation
		Colorants, pigments: apple fruit extract, betanin, leghemoglobin, tomato juice, lycopene, carotene, green algae	Color, antioxidant, and antimicrobial
		Flavorings, seasoning: spices, herbs, HVP, yeast extracts	Flavor, aroma, taste, nutritive value, preservation
		Vitamins: vitamin B_1, B_{12}, B_3, B_6, sodium ascorbate	Nutritive value
		Minerals: Zinc, iron, calcium, selenium	Nutritive value

SCP single-cell protein, *HVP* hydrolyzed vegetable proteins

treatment of plant proteins could result in improving solubility, heat stability, and reduced allergenicity (Butré et al. 2012; Jeewanthi et al. 2015).

The texturization and structuring of plant proteins to a meat-like texture significantly affect the consumer's acceptance of meat analogs (Sun et al. 2021). The separation of protein-rich and water-rich fractions is the first step in fiber formation during the processing of proteins (Tolstoguzov 2006), and this process could be further sped up by adding some polymeric compounds (hydrocolloids or carbohydrates by increasing mutual exclusion among various polymers (Tolstoguzov 2003).

Extrusion cooking is the most commonly used technology for texturizing and structuring plant proteins while preparing meat analogs by passing them between dies at suitable pressure, moisture, and pressure conditions. Food products of various shapes and varieties are manufactured by modifying the size and shape of dies (Kumar et al. 2019). Hot extrusion is performed at 100 °C temperature, thus leading to a cooking effect that causes various chemical and structural changes in proteins.

These changes depend on various factors such as moisture content, barrel temperature, composition and quality of raw ingredients, protein content, particle size, barrel diameter, barrel temperature, extrusion rate, and pressure (Ryu 2020; Wild 2016). The high moisture extrusion is characterized by high heat transfer and lower mechanical dissipation due to a larger barrel surface (Wild 2016). It facilitates a high degree of texturization, elasticity, nutrient retention at lower temperatures, and elasticity but increases storage cost and, at the same time, reduces aroma and taste. At high temperatures, plant protein gets denatured, and screw rotation causes shear force leading to the unfolding of peptides and destruction of the three-dimensional structure of proteins. This leads to the formation of disulfide bonds and cross-linking between denatured proteins (Ryu 2020). However, the high energy usage, high cost of extrusion, and size constraints are challenges faced by the extrusion industry (Kumar et al. 2022d).

Other technologies used in the processing of plant proteins are spinning, 3D/4D printing, Couette shear cells, and freeze structuring. Under spinning, ultrathin fibers are produced from vegetable proteins to develop meat analogs. Further, the fiber characteristics vary with the spinneret's parameters (temperature, humidity, and distance between spinnerets to collectors), viscosity, surface tension, and conductivity (Moomand and Lim 2015). However, the high amount of waste generated during the process, the requirement of low pH, the application of additives, and high salt concentration make this process need to be addressed by the food industry.

Figure 1.2 represents the various steps in the processing of plant proteins into plant-based meat analogs.

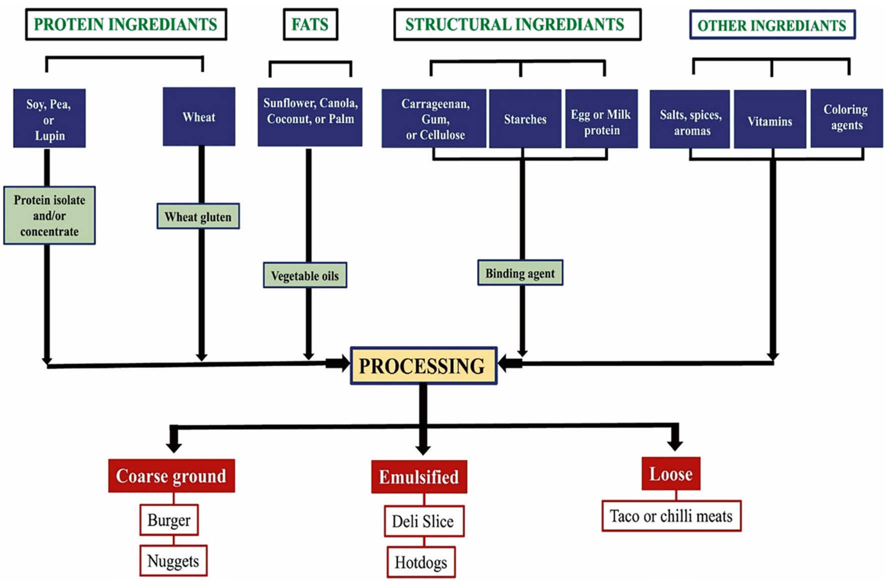

Fig. 1.2 Formulation of plant-based meat analogs. (Adapted from Ishaq et al. (2022). This article was published in Ishaq et al. (2022), Copyright Elsevier 2022)

1.5 Prospects and Challenges

The plant-based meat analogs have bright prospects due to their sustainability potential, lack of animal welfare and ethical issues, and ability to supply food for a burgeoning population with already strained resources. But to harness their potential, these products should be accepted among the broader population as meat substitutes.

1.5.1 Economics and Marketing

The price of meat analogs is comparatively lower than meat due to the use of cheaply available proteins, among which soy proteins still form the most commonly used source of protein in plant-based meat analogs (Kumar et al. 2023; Rubio et al. 2020). At the standardized cost based on 2009 data, (Lusk and Norwood 2009) noted a significantly lower per-gram price for plant proteins as compared to meat proteins, e.g., \$0.01/g for soybeans, \$0.03 for wheat) whereas \$0.22/g for pigs and \$0.12/g for chickens. However, this price depends upon several factors, and premium meat analogs usually cost more and maybe equivalent or higher to meat counterparts.

Unlike traditional meat, the post-processing cost is significantly higher for meat analogs (up to 94.3% of the total retail cost of crop products) as compared to 50% of the retail cost for beef (Lusk and Norwood 2009). In addition, to impart flavor, texture, and nutritional value to meat analogs, a range of additives, such as colorants, vitamins, minerals, lipids, etc., are added, consequently increasing the overall cost of production for these products (Tziva et al. 2020). However, we should note that with increasing incomes and lifestyles, premium meat analogs are also accepted by health-conscious and affluent consumers.

1.5.2 Consumer Acceptance

Consumer acceptance of food products is essential to get it popularized among consumers and its marketing. The consumer acceptance of meat analogs, similar to other food products, is largely affected by their organoleptic qualities and also price compared to their meat counterparts. The packaging also plays an important role in attracting consumer attention and creating interest in food products. Thus, using a proper packaging system enlisting its nutritive value, sustainable merits, and highlighting animal welfare compliance could result in higher consumer acceptance of the meat analogs. Similarly, consumer acceptance varies from region to region due to food habits, availability of dispensable income, and availability/exposure to typical food products. Thus, to improve consumer acceptance on a large scale, the imitation of common meat products resembling them in taste and other attributes could be a proper strategy.

The consumer acceptance of plant-based meat analogs was observed to be very high for China (95.6%) and India (94.5%), in comparison to the USA, where it was reported to be 74.7% (Bryant et al. 2019). The significant roadblocks in consumer acceptance among EU consumers were observed in the lack of familiarity and lower sensory attractiveness; thus, in these countries, a very close imitation of meat analogs to their meat counterparts could improve the marketing of these products (Hoek et al. 2011). The factors affecting the acceptance of meat analogs vary from country to countries such as in Germany and France, the issue of animal welfare and its positive impact on the environment and health are the main driving force, whereas, in the Netherlands, animal welfare, health, and lower-quality meat were identified as the main driving force for the adoption of meat analogs (Weinrich 2018). However, in all these above-mentioned three countries viz., In Germany, Netherlands, and France, the taste of meat analog is the key factor in determining consumer acceptance and other factors such as consumer habits, price competitiveness, and convenience (Schouteten et al. 2016). However, under emotional and sensory profiling under blind testing conditions, the plant burgers were awarded with 'distrust, disappointed and discontented' whereas meat burgers with 'happy, contented, and pleasant' by the 97 young adults, with an insect-based burger and plant-based burgers were having comparable liking (Schouteten et al. 2016).

Among various sensory attributes, taste is the most important criterion affecting consumer acceptance of meat analogs. As per the Mintel Store report on 'US plant-based protein report 2023', more than half (51%) of consumers surveyed were on the view that plant-based meat analogs should taste indistinguishable from their meat counterparts, followed by price (25%) concerns (Mintel Store 2023). Further, in the same report, consumers tried the meat analogs once or twice but did not follow them due to their taste, 46% followed by those disappointed due to these products did not meet the expectations of 35% of consumers.

Some meat products are highly processed to mimic the sensory, chemical, and physical attributes of meat. These novel meat analogs are considered by consumers to be 'highly processed' as compared to traditional burgers and thus considered an unnatural method of food production (Asioli et al. 2017). The negative marketing approaches such as preservative-free and antibiotic-free also have an impact on consumer acceptance. Thus, those consumers who have a liking for the 'clean label' have some concern for these products due to their unnaturalness (Asioli et al. 2017).

The consumer acceptance of insect-based meat analogs is challenging in societies where entomophagy is not generally practiced, such as Europe, North America, and India. This is due to entomophobia (fear and disgust towards insects), attachment to insects eating to low social strata with consideration of food of the poor, and neophobia (Deroy et al. 2015; Shelomi 2016; Van Huis et al. 2013).

1.5.3 Sensory Attributes

Appearance, flavor, and texture are the primary sensory attributes that determine the overall quality of the meat analogs. The flavor of meat is imparted by a unique combination of a range of compounds formed by the interaction of meat lipids, proteins, and minerals, and the muscle fibers in the meat form texture. The presence of heme pigments contributes to the color of the meat and meat products. An ideal meat analog product should mimic its meat counterpart in shape, convenience, texture, appearance, flavor, aroma, and nutritive value.

For imparting the red color of fresh meat to meat analogs, various plant extracts and juices such as apple extract, tomato juice, carrot juice, beet juice, carotene pigments, or recombinant heme protein sourced from soy expressed in *Pichia pastoris* as soy-leghemoglobin are used. The merit of leghemoglobin is that it forms a brown color upon cooking the product, similar to meat products (Jin et al. 2018). Further, it also improves the flavor profile of meat analogs (Fraser et al. 2018; Kyriakopoulou et al. 2021). Vegetable proteins are texturized to give texture and functional properties similar to meat by applying mechanical, thermal, or shear pressure, such as various extrusion, shear cell technology, 3D/4D printing, and other technologies (Kumar et al. 2022c). Plant lipids such as coconut oil and cocoa butter are used in meat analogs to give smoothness, taste, texture, and flavor to meat products (Rubio et al. 2020).

Various additives (3–10%) are added to the meat analogs preparation to mimic the flavor as well as to mask or modify the flavor (Asgar et al. 2010). Several plant proteins have inherent bitterness and astringent taste, which further make the selection of ingredients for the preparation of meat analog very crucial. Alternatively, by adopting advanced processing technologies, this bitterness and astringency could be modified. Soy protein has beany and grassy flavor due to the presence of isoflavone, lipoxygenase, and saponin compounds, which can be mitigated by soaking or heating (Kumar et al. 2012, 2017, 2023). However, the increasing processing levels decrease the nutritive value and, thus, the need to compensate for these nutrients by adding higher amounts. The application of filamentous fungi provides meat-like microstructure to mycoprotein-based meat analogs such as Quorn™ (Joshi and Kumar 2015; Kumar et al. 2011; Wiebe 2002).

Texture and flavor are the two main factors that determine the consumer acceptance of meat analogs. The application of high-moisture extrusion is widely used to develop fibrous and meat-like textures to plant proteins (Palanisamy et al. 2018; Ryu 2020). These texturized proteins are used as meat analogs to impart texture and appearance similar to meat. The structure and composition of the meat analogs have an effect on flavor either by retention by entrapment of volatile compounds or by the specific chemical or non-chemical interactions/bindings between the ions, water molecules, and large food molecules (Wang and Arntfield 2017). During high thermoplastic extrusion, the volatile compounds are lost in steam at the time of expansion of materials immediately after coming out from the die, thus leading to poor flavor scores (Yuliani et al. 2004). Various factors that affect the flavor of meat analogs are raw ingredients used, extrusion conditions such as time, temperature, pressure, and moisture content, size of the end product, vapor loss during expansion, and nature/diffusability of volatile compounds (Bhandari et al. 2001; Reifsteck and Jeon 2000).

As such, food proteins do not have any prominent flavor, but at high temperatures, proteins form bonds with flavor compounds (Wang et al. 2017). Thus, upon altering the protein's ability to bind with the aromatic compounds, the flavor of the food products is also altered (Guichard 2006). Interestingly, this binding of protein to aromatic compounds is reversible and comprises hydrogen and hydrophobic bindings (Farrell et al. 2002), which have a direct impact on the desirable flavors (Wang and Arntfield 2017). Further, meat analogs developed by using various combinations of soy proteins having wheat gluten from 10% to 40% and moisture content varies from 50% to 80%; the highest flavor retention was measured with the product having the highest wheat gluten and minimum moisture (Guo et al. 2020). Further, the authors (Guo et al. 2020) the alteration of microstructure upon increasing wheat gluten content in product with the most common compounds affecting flavor as alcohols, esters, phenols, alkanes, and alkenes (Guo et al. 2020).

There is a need for a cluster-specific/region-specific approach while considering the consumer acceptance of meat analogs, as a study by Lemken et al. (2019) reported the consumer acceptance of legume-based meat analogs in New Zealand, whereas in another cluster, a substitution of legume in meat products was preferred. Similarly, a higher acceptance for plant-based meat analogs was reported in North Belgium, especially among youths and women, but highlighted the need for more varieties and better imitation of meat products (Bryant and Sanctorum 2021). Further, to increase consumer acceptance of plant-based meat analogs, there is a need to develop, market, and promote plant-based meals and plant-forward living based on consumption orientation rather than opposing meat consumption (Graça et al. 2019). Among Danish consumers, negative attitudes toward high meat consumption towards satiety effect, taste, protein content, and environmental and health effects were reported as the main limiting factors in adopting a plant-based diet among these consumers. Whereas consumers having low-meat intake are more attracted to plant-based diets (Reipurth et al. 2019).

The consumer acceptance of meat analogs could be further increased by appropriate marketing strategies highlighting the nutritive role, environmental impact, and positive health effects of the consumption of meat analogs. Giving more front space in supermarkets and placing them next to equivalent meat products could also increase consumer interest and facilitate the transition from meat to plant-based diets. An increase of 67% in meat alternatives sales was recorded by this marketing intervention (Coucke et al. 2022).

Various prospects of plant-based meat analogs are presented in Fig. 1.3.

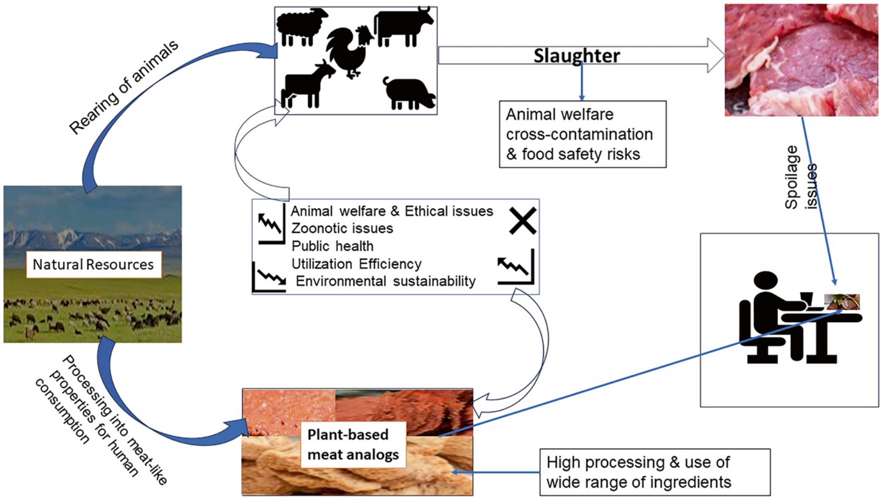

Fig. 1.3 Prospects of development of plant-based meat analogs

1.6 Impact of Meat Analogs

The popularization and adoption of plant-based meat analogs in diets would have a major effect on the environment, public health, animal welfare, and food security.

1.6.1 Environmental Impact

As the environmental impact of meat analogs (plant and insect-based meat alternatives) is markedly lower than that of conventional meat, thus, a reduction in meat production and consumption could have a positive effect on the environment. Even the environmental impact of the animal product with the lowest environmental impact among animal products is higher than the meat analogs (Poore and Nemecek 2018). Increasing red meat production has created newer challenges in the form of rapid conversion of forests into agriculture to produce more feed and grains (deforestation), emission of greenhouse gases leading to climate changes, water pollution, and eutrophication (Poore and Nemecek 2018). This highlighted the importance of the immediate dietary shift towards more environmentally friendly and healthy plant protein-based substitutes from meat and meat products.

A 50% substitution of meat and dairy by 2050 with plant-based meat analogs could stop the deforestation of land and reduce greenhouse gas emissions by 31% as compared to 2020 levels (Kozicka et al. 2023). Among all animal products, replacement of beef was reported to have the highest environmental impact. Interestingly authors pointed out that by restoring the agricultural land to forest, the environmental benefits could be further improved by 92% (Kozicka et al. 2023). Thus, plant protein production has higher environmental and economic merits due to its comparatively lower uses of environmental resources and lower cost of production.

Various LCA (life cycle assessment) studies highlighted the importance of using fermentation-derived microbial proteins, such as microalgal proteins, by using bioreactors due to their high production efficiency, minimal environmental impact, and an excellent source of nutrition (Becker 2007; Kumar et al. 2022d; Wells et al. 2017). For example, a 20% per capita replacement of red meat (beef) on a protein basis with microalgal proteins worldwide by the year 2050 would half the carbon dioxide emission and deforestation, increase the pasture cover, and reduce the emission of greenhouse gases (Humpenöder et al. 2022). Further authors (Humpenöder et al. 2022) also highlighted the challenges of the non-linear saturation effect on deforestation and emission of greenhouse gases in the prediction of environmental benefits based on the LCA method.

Overall, the environmental merit of the meat analogs depends upon the raw ingredients used and the level of processing used during their manufacture. Based on LCA assessment, plant-based beef analogs produced by Beyond Meat® and Impossible™ Foods have a lower environmental impact, such as significantly lower land usage and water eutrophication as compared to their beef, pork, and chicken counterparts, whereas, in terms of energy usage, the meat analog exceeds the energy usage of pork and chicken. Further, the greenhouse gas emission was calculated as lower than pork and beef but higher than chicken (Heller and Keoleian 2018; Khan et al. 2019).

The Beyond burger (1/4 pound) was calculated to emit 90% less greenhouse gas emission, 93% less land usage, 46% lower energy requirement, and more than 99% less water requirement as compared to its beef counterpart having the same weight (Heller and Keoleian 2018). Further, in this burger, the major ingredients used (pea protein, coconut oil, and canola oil) are mainly responsible for greenhouse gas emissions and land and energy usage. The polypropylene tray used for packing these products also has an environmental effect, and a 100% recycling of this tray has the potential to further reduce greenhouse gas emissions by 2% and energy usage by 10% (Heller and Keoleian 2018). Similarly, the Impossible Burger® has 87–96% lower environmental impact (87% less water usage, 96% less land usage, 89% lower greenhouse gas emission, and 92% less eutrophication) as compared to conventional ground beef burgers (Khan et al. 2019). However, the ingredients have a major environmental impact, while the packaging of the product was reported to have a negligible impact on eutrophication, water and land usage, and emission of greenhouse gases (Khan et al. 2019).

In terms of energy and land footprint, mycoproteins (Quoron™) are more efficient than Beyond Meat® and Impossible™ burgers. The water footprint of the plant-based meat analogs mainly depends upon the major plant protein present in these products. Based on the LCA, mycoprotein was observed to have a water footprint of 40 kg/kg of mycoprotein which stands very high as compared to other common sources of plant proteins such as wheat gluten with 0.954 kg/kg and soy protein as 0.73 kg/kg (Smetana et al. 2015). Further, Fresán et al. (2019) calculated the water footprint of 39 meat analog products and reported 3800 m^3 of water consumption for the production of 1 ton of plant-based meat analog products, with a major chunk of this water is used during the harvesting of protein sources.

Thus, there is an urgent need to mitigate the environmental impact of the producers by following a multi-pronged or holistic way. Even the communication for the lower environmental impact to the consumers is equally important to increase consumer acceptance, thus making it more economically viable.

1.6.2 Impact on Employment

The development and popularization of meat analogs/alternatives might have an effect on the agriculture sector and, more specifically, on meat production practices, consequently impacting social and cultural aspects. As this sector is still in the growing phase and still remains to tap the actual potential, the exact effect on agriculture, social, and cultural aspects is yet to be clear. The job profile of conventional meat production is different than the production of meat alternatives. As in livestock rearing and meat production practices, with job profile can be suited for semi-skilled or trained personnel. However, the production of meat analogs warrants the application of advanced technologies and the application of a number of additives in a specific manner to get the desired attributes in the developed meat analogs. Thus, the meat analogs are expected to create new employment for skilled and highly skilled jobs. However, the actual impact may vary with the geographical locations and place to place due to differences in the production systems. In a study conducted among experts in Brazil, the USA, and Europe, (Morais-da-Silva et al. 2022) reported pressure on animal farmers due to the fast transition, with the Brazilian farmers being more positive/optimistic about the meat alternatives in creating new job opportunities.

1.6.3 Impact on Public Health

Although meat is an important source of high-quality nutrients its overconsumption of meat, especially red and processed meat, has been correlated to various health issues. Overconsumption of cured and processed meat products has been linked to colorectal cancer and cardiovascular diseases (Badar et al. 2021; Bouvard et al. 2015; Domingo and Nadal 2017). This could be due to high salt intake and high levels of processing, risking the formation of carcinogenic compounds. Meat is deficient in dietary fiber and antioxidant potential, which are abundantly present in vegetables (Kumar et al. 2020b).

The vegetarian diet was reported to exert higher health benefits and provide protection against such as from cardiovascular diseases, metabolic conditions, cancers, and mortality. In addition, it also offers protection against obesity and diabetes (type-2), with higher positive effects recorded in males rather than females (Le and Sabaté 2014). However, plant foods also lack some important nutrients (vitamin B_{12}, long-chain $n-3$ fatty acids, retinol) and thus need a careful approach while formulating plant-based diets (Sun 2021). The clinical trials conducted by the Stanford School of Medicine also demonstrated that lower serum trimethylamine-N-oxide levels in the blood lead to reduced risk of cardiovascular diseases (Crimarco et al. 2020). Thus, the consumption of plant-based foods and the reduction in red and processed meat consumption are included in most dietary guidelines for hypertension, obesity, and reducing cholesterol (Craig and Mangels 2009).

Meat is an excellent medium for the growth of food spoilage and pathogenic microorganisms. Further, various steps during the production of meat and post-slaughter processing by coming in contact with contaminated water, packaging, contaminated surfaces, etc., also increase the risk of contamination of pathogenic microorganisms such as *E. coli*, *Campylobacter*, *Salmonella*, *Staphylococcus aureus*, *Shigella*, *Listeria monocytogenes*, *Yersinia enterocolitica*, etc. In addition, the oxidation of meat lipids and proteins also reduces the storage life and spoilage in huge quantities, leading to substantial environmental costs during production, and environmental pollution. The non-judicious use of antibiotics in animal treatment and as feed additives also leads to the entry of antibiotics into the food chain and increases the risk of antimicrobial resistance (AMR). Interestingly, the issue of spoilage, growth of pathogenic microorganisms, and application of antibiotics are comparatively lower than these incidences in meat production. Antibiotic usage in agriculture in the USA was reported to be minimal with only 0.12% of animal agriculture (Stockwell and Duffy 2012).

1.6.4 Impact on Animal Welfare

Due to their production nature, the meat analogs production process does not involve animal rearing and is thus free from any ethical and animal welfare issues. These products are free from animal byproducts except the dairy and egg-based meat analogs or additives. The treatment meted out to animals during the rearing and meat production remain major concerns due to the intensive rearing practices, managemental practices (such as tail docking, dehorning, beak trimming, early weaning, etc.), stress, pain, and distress during transportation and slaughtering operations. The production of plant-based meat analogs would have a direct impact on animal welfare by avoiding these issues. Further, there is an indirect benefit on animal welfare by the substitution of meat with meat analogs, that is by preventing degradation of forest lands and reforestation leading to better animal welfare of wild animals and preservation of biodiversity.

However, this should be noted that in the case of preparation of insect-based meat analogs, there is a concern for animal welfare during their harvesting. There should be proper handling during their harvesting and it should be specific for species types and insect growth stages (Adámková et al. 2017). Some of the humane methods for killing insects are fast-freezing and boiling water (Adámková et al. 2017). Ensuring proper management practices during insect rearing and harvesting would have a positive impact on their growth and productivity in addition to increasing the acceptance of insects as food (De Goede et al. 2013).

1.6.5 Nutritive Quality and Food Safety Issues

At present, the main component of meat analogs remains protein, lipid, and moisture in addition to the addition of several vitamins, trace minerals, colorants, flavorings, and additives. At present, soy and wheat gluten remain the main source of protein in plant-based meat analogs, with an increasing trend in the utilization of pulses/legumes, non-conventional protein sources, fungi, and SCP (Kumar et al. 2017; Kyriakopoulou et al. 2019). The nutritive value of meat analogs is affected by the formulations and composition of these products.

Plant-based meat analogs could be prepared as per the desired nutritive quality by proper selection of raw ingredients and processing technologies. Further, a high level of processing is performed to get the meaty texture of plant proteins. The exposure to high temperature and pressure applied during processing may cause loss of nutrients and nutritive quality of some ingredients. Thus, plant-based meat analogs may have lower nutritive quality than raw ingredients, which needs to compensate for these losses.

The increased consumption of these ultra-processed food products in place of unprocessed/whole food could cause nutritional deficiencies (Hall et al. 2019; Moodie et al. 2013). Further, in an effort to closely mimic the nutritive and organoleptic attributes of meat, some synthetic or animal-origin additives are used during the preparation of plant-based meat analogs. This warrants proper labeling information on the product packages to develop consumer confidence (Choudhury et al. 2020). The food safety concerns are more with respect to the use of single-cell-proteins (SCP) and insect-based meat analogs. These two sources are considered highly efficient in production and environmental sustainability.

Insects, mainly due to their growing ability on wastes and hazardous materials and as a survival strategy under hostile conditions, accumulate allergens, toxins, and anti-nutrient substances (Meyer-Rochow et al. 2021), in addition, being a carrier/vector of pathogens. A higher amount of these toxins, allergens, and anti-nutrient factors are noted when insects are reared on poor quality food sources such as solid wastes, and pollutants (bioaccumulation), and these substances in insects could be controlled by rearing on food sources free from these compounds (Kumar et al. 2022d). Phytates, oxalates, hydrocyanides, tannins, heavy metals, and cyanogenic glycosides are some common anti-nutrients present in insects. These compounds, however, are well below the toxic levels in insects, interfere with the absorption of nutrients in our gut, and could adversely affect human health (Ekop et al. 2010; Omotoso 2006). Further chitin, forming the exoskeleton of the insects, could only be digested in countries (mostly tropical countries) where there is a tradition of entomophagy (the practice of eating edible insects) due to the presence of chitinolytic enzymes secreted by gut microbiota (Finke 2007). Similarly, the consumption of African silkworms causes thiamine deficiency due to the presence of thiaminase enzyme in these insects, thus requiring proper heat treatment before consumption to neutralize it (Nishimune et al. 2000).

Some SCP sources are also having issues of accumulation of heavy metals, pesticides, toxins and allergens (Putten et al. 2011). The endotoxin released by fungi and bacteria also poses health risks e.g., aflatoxins by *Aspergillus flavus*. The presence of a high amount of nucleic acid (upto 16% of dry weight) in bacterial SCP could pose a risk of kidney stones and gout due to the conversion of nucleic acid into uric acid (Bux and Chisti 2016). Some microalgae also pose neurotoxins and hepatotoxins, such as microcystin hepatotoxin by Cyanobacteria may risk liver cancer (Testai et al. 2016). Similarly, the presence of some neurotoxins, such as anatoxins and saxitoxins in *Anabaena*, *Aphanizominon*, *Oscillatoria*, and *Trichodesmium,* may risk food poisoning (Mulvenna et al. 2012).

1.7 Conclusion

At present, plant-based meat analogs for beef, pork, and chicken are becoming popular, and various types of these products are widely available in the market. The plant-based analogs for seafood are still in the developing phase. To increase the consumer acceptance and economics of the analogs, these products should be formulated and processed to remain indistinguishable from their meat counterparts in taste, color, texture, and nutritive value. There is a need to have uniform regulatory frameworks to facilitate easier global growth and trade among countries. The high level of processing for texturizing and structuring plant proteins similar to meat proteins and the addition of various additives to improve flavor, color, and nutritive value lead to various issues of food safety, lack of consumer confidence, increasing cost, clean labeling, sustainability, loss of nutritive value, and permissible limits in the development of plant-based meat analogs.

To reduce the cost and improve the sustainability of plant-based meat analogs, it is of utmost importance to use non-conventional sources of vegetable proteins such as mycoprotein, single-cell proteins (SCP), grass, leaf proteins, agriculture industry byproducts that are yet to be harnessed and have high environmental and nutritive benefits. There is a need to follow a cluster/region-specific approach and proper packaging and marketing strategies to make this product popular among the masses.

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