

GREEN FOODS AS SUSTAINABLE MEAT ALTERNATIVE: A REVIEW

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Abstract

Green food is a term related to plant-based food having properties similar to meat. The rising environmental and health concerns are the main driving forces of consumer preference for sustainable plant-based meat over animal meat around the world. Proteins needed for meat analogue development can be of plant, algae, fungi or bacterial origin. The ingredients like hydrocolloids, smoke flavourings and spices can be added to improve texture and flavour profile of products. Though commercial meat analogues of isotropic nature are manufactured by conventional extrusion technique, advanced technologies like shear cell and electrospinning can make fibrous yet tender anisotropic products that resemble very close to animal meat. The rising consumer demand for meat analogues allows a great market opportunity for manufacturers to sell products with various positioning claims like plant-based, vegetarian, high in protein, environment friendly etc. This review elaborates on ingredients and technologies used for the development of meat analogues. Also, the market potential and the feasible solutions for challenges and constraints faced by industries are discussed

Keywords: Meat analogues, Texturized vegetable protein, Hydrocolloids, Extrusion

Introduction

Food security can be defined as the state in which all individuals have access to adequate and safe nutrition consistently. The pressing issues of rapid population growth and global warming have placed immense strain on food security. While the concept of sustainability in food may not be as conspicuous as environmental sustainability on a larger scale, there is ample opportunity for nations worldwide to adopt a more resolute stance on sustainable

solutions in the food industry. (Datar and Betti, 2010). Animals are commonly reared in substantial quantities, specifically to facilitate meat production. The suboptimal exploitation and transformation of plant-based proteins into animal-based proteins during the food chain processes culminates in a reduction in value. In comparison to other food-related sectors, the meat industry notably contributes to the augmentation of Carbon-dioxide

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levels (Raney *et al.*, 2009). The utilization of resources such as water, feed, and electricity in animal husbandry and meat production is considerably high. Moreover, aside from its environmental implications, animal meat cannot be deemed as a sustainable food source that can meet the demands of the steadily increasing global population. Due to the elevated water activity of meat, it is more susceptible to microbial spoilage, leading to a substantial portion of produced meat being wasted. The negative impact of this wastage is not limited to just carbon footprint, but also extends to food security.

Plant-based meat substitutes have been identified as healthy sources of protein compared to animal meat, offering social, environmental, and health benefits. These substitutes may play a role in reducing meat consumption and promoting sustainability (Profeta *et al.*, 2021). Research shows that consumers who are not interested in vegan or vegetarian alternatives to meat may be open to trying meat blended with plant-based proteins, known as meathybrids. These products replace only a fraction of the meat with plant-based proteins. The choice to consume meathybrids is influenced by health perception, with healthier options being preferred. This self-centric motive seems to outweigh altruistic motives such as animal welfare or environmental concerns when choosing this new product category (Profeta *et al.*, 2020). More than fifty percent of consumers substitute meat at least occasionally, indicating a potential consumer preference for sustainable plant-based meat alternatives.

Meat analogues offer a more sustainable alternative to meat, with benefits such as reduced ecological impact and improved nutritional profiles (Cornet *et al.*, 2021). They can be produced using various ingredients, such as pea protein, soy protein, oat protein, and microalgae, which contribute to the texture, taste, and appearance of the analogues (De angelis *et al.*, 2020). The addition of these ingredients can create fibrous structures and enhance the physical properties of the analogues, making them more similar to meat. Furthermore, the control of water uptake and cross-link density in meat analogues can improve their water holding capacity, juiciness, and sensory characteristics (Caporgno *et al.*, 2020). These advancements in meat analogue production can help meet the growing demand for alternatives to animal proteins, providing consumers with plant-based options that mimic the texture, appearance, and taste of meat. The need for meat analogues arises from the increasing awareness of inefficient meat production and its impact on global food security (Beniwal *et al.*, 2021). With the rising population, there is

a growing discussion around the need for sustainable protein sources and meat replacement (Banovic and Sveinsdóttir, 2021). Meat analogues offer a more sustainable alternative to meat, and their production can help reduce the environmental impact of animal-derived protein foods. These analogues aim to mimic the texture and sensory attributes of meat, providing consumers with a similar experience (Dekkers *et al.*, 2018). The acceptance of meat analogues by consumers is influenced by their attitudes towards the main ingredients, such as rapeseed protein.

In contrast to the past, where consumers primarily considered intrinsic quality attributes such as sensory experience, safety, shelf-life, and packaging when purchasing meat, modern consumers are now more concerned with extrinsic qualities like organic production, animal welfare, fair trade practices, and environmental impact due to the saturation and abundance of food choices available on market shelves. The meat industry has been marred by negative attention due to the exposure of unethical, unsafe, unhygienic, and non-standard practices in some animal slaughterhouses, brought to light by social media and animal rights movements. Additionally, there is a growing concern about the primary production methods used in animal food production, and a lack of sufficient information on the labels of market-available animal meat products has decreased their acceptability.. Multiple consumer studies, which have focused on various demographics, have indicated a growing inclination towards plant-based, green foods. The aforementioned reasons have been cited as the driving force behind this shift in the perception of quality. (Asgar *et al.*, 2010).

Green foods, which are predominantly derived from plant sources like soybean, pea, and other legumes, have come to define a notable shift in consumer preference towards plant-based foods over recent years. This trend can be attributed to a heightened awareness of health and environmental consciousness among consumers. Notably, the growth of plant-based meat analogues or texturized vegetable proteins has been remarkable. By effecting chemical/mechanical/thermal modifications on the functionalities of globular proteins in plants, a texture and mouth feel similar to animal proteins can be delivered. Furthermore, legume-based meat, derived from proteinaceous legumes that can grow under extreme biotic and abiotic stress conditions, is a more affordable source of protein than animal meat. Different shapes, such as sheets, patties, and strips, can be produced using extrusion-based technologies to create meat analogues (Ahmad *et al.*, 2022).

The Historical and cultural significance of utilizing plant sources as an alternative to meat and dairy products cannot be ignored. In many tropical countries such as Africa and India, legume-based vegan products are considered to be the 'poor man's meat' due to their ability to help overcome severe droughts and famines at different timescales. Moreover, during World War II, mock foods were used as approximate representations and replacements for meat, ultimately leading to a shift in the cultural significance of certain meals in the Australian diet. As a result, dishes like faux chicken and mock cream gained immense popularity among people (Samuelsson, 2020). Buddhist cuisine is well-known for its skillful utilization of tofu or gluten-based substances in preparing vegetarian diets that possess an exceptional taste profile similar to that of meat. Several restaurants located within or in close proximity to Buddhist temples in Japan provide a variety of imitation dishes such as vegan chicken, vegan goose, vegan duck, and vegetable fish (Son and Xu, 2013). A broad spectrum of distinctive commodities belonging to the plant-based meat analogues grouping can be attained through the amalgamation of a cluster of hydrocolloids and flavourings (Sun *et al.*, 2015).

Although the utilization of plant-based meat is undoubtedly a sustainable solution, various food processing industries are encountering significant challenges in replicating the characteristic structure of animal-based meat. However, by meticulously selecting the appropriate functional ingredients and optimizing the process conditions, it is plausible to achieve the desired fibrous yet tender properties synonymous with meat (Boukid, 2021). This review by He *et al.* (2020) caters to both flexitarians and conscious meat eaters by focusing on alternative proteins and other ingredients needed to formulate meat analogues using appropriate technology. Additionally, the review includes a market analysis of recently launched mock meat products in India, along with an overview of the challenge

The consumption of animal meat has been identified as the primary instigator of numerous occurrences of food-borne infections, including but not limited to Salmonellosis, and resulting intoxications. Furthermore, long-term ingestion of animal meat has been linked to an increased likelihood of colon cancer. The elevated levels of saturated fat and cholesterol present in meat have been identified as contributing to the development of several lifestyle disorders such as obesity, as well as diseases such as atherosclerosis. In some countries EU like the Council Directive 96/22/EC prohibits the use of beta-agonists and other substances with hormonal or thyrostatic action in livestock farming, as their action may be dangerous

for consumers and may also affect the quality of food-stuffs of animal origin. Also, the antibiotics and hormone regulators injected into animals (Viegas *et al.*, 2012) and study by Pleadin *et al.* (2019) reported that the potential health risks associated with the consumption of animal products containing hormones, both natural and synthetic which can be potentially inducing a reason for health issues. Maternal consumption of beef containing higher testosterone levels has been linked to impaired reproductive abilities in grown men, while milk consumption has been associated with a higher risk of premature menarche, the development of ovarian, prostate and breast cancer, and numerous reproductive disorders. Therefore, the use of hormones in food-animal production poses a direct consumer health risk. Moreover the study by Millstone and Lang (2018) states that evidence showing meat produced using key hormone, 17 β oestradiol, increases the cancer risk to consumers. Also, the antibiotics and hormone regulators injected into animals reduce the acceptability of meat by consumers, from a safety point of view (Bruinsma, 2009).

Protein sources

Algal protein

Algae are a rich source of proteins and other nutrients. They have the needed physicochemical properties to be utilized as a food component. Algae can be utilized as a source of protein in the preparatory work of vegan alternatives. However, challenges like major variations in protein content and composition depending on the species, season, temperature, and harvesting area exist (Joubert and Fleurence, 2008; Kumaraguruparaswami *et al.*, 2022). Algal protein extraction is still in its early stage and most of the techniques that have been created face issues with scalability (Harnedy and FitzGerald, 2011). The market competition of microalgae species and seaweed in comparison to other market sources is a crucial factor that will impact their commercial viability. More research is required to create new methods for lowering the costs of algal protein extraction and purification before it can be utilized commercially in meat analogues (Bhuva *et al.*, 2021).

Algae proteins are generally regarded as safe and are used as supplements and as food ingredients (Kurek *et al.*, 2022). Proteins derived from microalgae have desirable functional characteristics like solubility, emulsifying ability, foaming ability, and gelling ability. The solubility of protein from *Chlorella protothecoides* is 84.3% at a wider pH range (2-12). In comparison, soybean

protein (glycin) is soluble at much less than 20% at pH around 4-5. (Grossmann *et al.*, 2020). Caporgno *et al.* (2020) stated that inoculation of soybean with microalgae *Auxenochlorella protothecoides* creates texturized meat with increased vitamin B and E levels. Microalgae addition has also increased the level of lutein (0.6%) and zeaxanthin (0.3%). Microalgae such as spirulina (*Arthrospira platensis*) was studied for their foaming property compared to whey protein isolates at different levels of pH and it was concluded that algal protein can be a potential foaming agent. It is possible to replace soy-based products with spirulina to have a firm texture and fibrous products with fewer algae flavour (Grahl *et al.*, 2018; Buchmann *et al.*, 2019).

It is reported that vegetable proteins can be optimally blended with novel proteins like phycoprotein, mycoprotein and other bacterial fermentation-derived proteins which ultimately lead to the way of cellular agriculture in the future (Kyriakopoulou *et al.*, 2021).

Plant proteins

Soybean (*Glycine max*) is a versatile leguminous crop that has long been utilized in various cultures in forms like soymilk, tofu, and fermented products. Recently, its popularity has soared as an affordable and high-quality protein source for humans (Fukushima, 1994). To mimic coarse ground meat, manufacturers commonly combine both textured and non-textured soy proteins. Textured proteins encompass textured soy flours, textured soy concentrates, and a textured composite mixture of soy and wheat proteins. What sets textured soy protein apart is its unique ability to replicate the texture of meat when hydrated, along with its well-balanced amino acid composition that rivals that of animal proteins in terms of protein quality. Generally, quality of the plant protein (Olu and Adediran, 2015) depends on the balance among the minimum of nine essential amino acids, on which the bodily utilization of the protein depends. The nutritional quality of the proteins of most foodstuffs is dependent largely on two essential amino acids, lysine and tryptophan. However, methionine, threonine, and isoleucine may also be quite low in several plants. These amino acids are frequently referred to as the critical amino acids, the most deficient in relation to the standard protein being called the first-limiting amino acid. Therefore, the evaluation of protein quality is dependent on the quantity and balance of these essential amino acids. The soy protein concentrate is produced through a process of aqueous alcohol extraction, resulting in a product that contains approximately 70% protein content. The remaining portion consists of various compounds such as

starch, fiber, minerals, vitamins, and more. In contrast, soy protein isolate is created through alkaline extraction followed by precipitation in acidic conditions, leading to a product with a protein content of 90%. One notable advantage of soy protein isolate is its light color and mild flavor, which sets it apart from other soy ingredients (Cheftel *et al.*, 1992; Geerts *et al.*, 2018).

The utilization of legume protein as an ingredient in processed foods has seen a significant increase in recent years, driven by motives such as nutritive value, mouthfeel, functional properties, and economic considerations (Riascos *et al.*, 2010). Pea-based structures, for example, tend to be softer compared to soy-based products. To address this, researchers are exploring ways to enhance gel strength by modifying protein bonding. This can involve adding salts with chaotropic ions or optimizing conditions such as pH, temperature, and protein content (Sun and Arntfield, 2012). In addition, studies on Chickpea, lentil, and lupine have revealed their impressive emulsion and foam stabilization capacities. Moreover, by thermally modifying the proteins to enhance hydrophobic interaction, these legumes can also act as effective gelling agents (Bader *et al.*, 2011).

Oilseed proteins are categorized as biologically active proteins (enzymes), storage proteins, as well as structural proteins. Storage proteins are the most common and in high concentration in oilseeds. Protein levels are in the range of 13% to 17% for safflower, 23% for cottonseed and nearly 25% for rapeseed (Asgar *et al.*, 2010). Under low salt concentrations, canola protein fractions, mainly albumins and globulins, can form cohesive gels. In some cases, it forms strong and flexible networks when canola protein was mixed with k-carrageenan. This indicates that canola protein is a better structure former (Uruakpa and Arntfield, 2004). Proteins can be extracted from the de-oiled or defatted seed cake from the oil manufacturing industry. The whole oil seed cake can also be processed into dry flour formats after many treatments to ensure safety and quality.

Wheat gluten is another commonly used plant protein. It is insoluble in water. When extended, it naturally forms thin protein films which can be easily converted into fibrous proteinaceous materials. Zhang and Zhang (2022) discuss the preparation method of wheat gluten protein nanofibers through electrostatic spinning. The study also highlights the advantages of these nanofibers, such as water stability, antibacterial function, biocompatibility, and biodegradability. Some studies shows that the practical implications of enzymatic glycosylation can be used to improve the mechanical properties of protein fibres made from

wheat gluten The improved properties of the fibers could lead to the development of stronger and more durable products which were reported by (Lei *et al.*, 2021). Study by Saleh *et al.* (2018) undertook steps like solubilising fibrous protein by contacting it with an alkaline solution, aging the resulting mixture to form a homogeneous solution, and coagulating the resulting solution to form the proteinaceous material. Glutenin and gliadin proteins of wheat gluten are responsible for elasticity and extensibility respectively. These distinguishing characteristics are the result of molecular properties and mesoscopic behaviour which results in the use of gluten as a key ingredient in the formation of fibrous and viscoelastic structures (Don *et al.*, 2003).

Other ingredients and additives

Only a lesser amount of fats and oils are used in meat analogues for lubrication during extrusion and better mouthfeel. Cheftel *et al.* (1992) suggested that oil of more than 15% by weight should not be used in the formulation to avoid the slippery effect on extrusion. Moreover, the addition of oil/ fat components was known to enhance the flavour by retaining the volatile hydrophobic components in the oil and thereby reducing flavour loss during processing (Resurreccion, 2004).

Hydrocolloid-based binders like xanthan gum, carrageenan, and methyl cellulose can be added. The addition of Methylcellulose (1.5-4%) to commercial texturized vegetable protein and textured soy protein isolate-based formulation increased texture profiles like hardness, gumminess and chewiness of meat analogue. However, the water absorption capacity of meat analogue steadily reduced with an increase in methyl cellulose concentration (1.5-4%). Regardless of methyl cellulose concentration, the redness and lightness color value of meat is reduced upon cooking. Still, a visible improvement in structural integrity after cooking could be seen with an increase in methylcellulose amount. Based on sensory qualities, 3% methylcellulose was found optimum for addition into meat analogues. Unlike animal meat, textured soy protein-based meat analogue with added methylcellulose had shown significantly reduced shrinkage upon cooking (Bakhsh *et al.*, 2021). Wheat gluten serves as a good binder and also reduces cooking loss during preparation. Better dough handling properties and the cohesive and viscoelastic behaviour of wheat gluten improve the functional properties of meat analogues (Asgar *et al.*, 2010; Malav *et al.*, 2015). The gelling and thickening behaviour of hydrocolloids can be exploited as a fat substitute in meat products. It also

forms a less porous barrier on the surface that can reduce oil absorption during frying of meat (Dekkers *et al.*, 2016). It was reported that a combination of sorghum flour, finger millet flour and carrageenan can be used as a fat substitute in chicken patties with no significant difference in texture profiles, sensory, water holding capacity, pH and moisture (%) (Das *et al.*, 2015). It can be said that fat-reduction technology can be applied in meat analogues using hydrocolloids.

To enhance the flavour and aroma of the final product, industries use spices and condiments. The seasoning formulation as per the regional taste can be designed and used for enhancing consumer acceptability. Smoke flavourings would add extra benefits by mimicking the flavour profile of grilled/smoked animal meat. Also, industries are focusing on the creation of novel ingredients, for example, heme, a molecule responsible for the preference, color and iron content of meat (Choudhury *et al.*, 2020). On the other side, mushrooms can also be used in the formulation due to the presence of biologically active components and meat-flavoured sulphur compounds and amino acids (Kumar *et al.*, 2017). Arora *et al.* (2017) developed mushroom-based sausage analogue with binding agents. The addition of 0.8% carrageenan to analogue significantly reduced cooking loss and improved emulsion stability, whereas casein gave inferior sensory qualities.

Several food companies produce plant-based products that resemble the meat structure and taste properties. The ingredients used in formulation vary with the company and variant of the product. The advancements in the production and preparation of meat substitutes have facilitated the use of even alternative ingredients such as lupin, faba beans and other oilseed crops such as sunflower and rapeseed. water, necessitating effluent treatment. Factors like solubility, viscosity, and conductivity impact electrospinning suitability (Heuvel *et al.*, 2013). Researches from Mattice and Marangoni (2020) have refined parameters to create uniform zein fibers with minimal ethanol consumption. Despite generating fine fibers, electrospinning has low throughput and production efficiency challenges

The utilization of these locally grown protein crops for meat analogues manufacture adds value to the crop and consequently supports the farmers.

Texturized vegetable protein technology

Meat analogues were produced by homogenization or by emulsification and large piece formation. To this an emulsifying agents such as proteins, particles, or surfactants were added and homogenized through high-speed mixing to shape

the structure which traps the fat and non-soluble elements. Pressure aligns the protein chains, forming a cohesive three-dimensional matrix. Heat induces the protein denaturation which leads to aggregation and coagulation ensuring the product's integrity. Extrusion cooking method is used for meat analogues (Kumar *et al.*, 2017). During the extrusion process, the ingredients flow steadily into the extruder at varying temperature and pressure conditions leading to the formation of a semi-solid product which maintains its moisture content. The typical steps for desired meat analogue have the specific type of Wet Textured Vegetable Protein (McClements *et al.*, 2021). Vate and Benjakul (2016) conducted research to optimize the texture of soy-based mock meat using extrusion. They found that the barrel temperature played a crucial role in determining the functionality and appearance of the product. Higher temperatures resulted in improved rehydration and increased water and oil uptake, but also caused the product to darken. Meat analogues are typically produced using a process called high moisture extrusion (HME), which involves subjecting protein-rich materials to thermal and mechanical pressures while maintaining a moisture content of over 40% (Witteck *et al.*, 2021).

The Couette cell can switch to continuous mode while still retaining the ease of use. This involves a lesser residence time of 20 minutes (Krintiras *et al.*, 2016). Researchers consistently worked to enhance the texture of plant-based meat analogues with diverse methodologies, notably the innovative shear-induced spinning technique introduced by (Li *et al.*, 2020) which operated at higher temperatures to decrease mixture viscosity can lead to protein unfolding, enhancing polymer flexibility. This consequential adjustment indirectly impacts phase separation and the deformability of dual-phase blends considering crucial parameters: process temperature, time, and shear rate, can significantly influencing shear-induced structuring (Dekkers *et al.*, 2016). The spinning technique intricately transforms concentrated vegetable protein into thin meat-like fibers. Electrospinning, powered by voltage differentials, involves acid, alkaline and solvents.

Future efforts should enhance the understanding for advanced electrospinning, potentially utilizing cost-effective vegetable proteins like soy, mushroom, and wheat gluten (Kołodziejczak *et al.*, 2021; Zahari *et al.*, 2022; Sharima Abdullah *et al.*, 2018). In a study by Nayak and Panda (2016), current market offerings primarily feature nugget-type meat analogues which showcase comparable textures between optimized fermented soybean and poultry meat post-solid-state

fermentation with *Rhizopus oligosporus* and powdered *Agaricus* mushroom integration.

Post-consumption characteristics of meat analogues

Meat analogues should not only focus on protein values but also consider the overall composition of the protein and their proportions for a balanced diet. They should have Protein Digestibility Corrected Amino Acid Score (PDCAAS) similar to that of meat. Soy proteins have higher PDCAAS scores. Alexander *et al.* (2017) reported that a higher PDCAAS score cannot be attained practically in the formulation without the use of soy protein. The other protein quality based on amino acid profile which referred by author (Olu *et al.*, 2015), indices such as bioavailability, biological value, net protein utilization, and protein efficiency ratio should also be compared when choosing the right protein ingredient for formulation.

The study done by Herreman *et al.* (2020) compared the quality of 12 plant-based proteins and 5 animal-based proteins based on their digestible indispensable amino acid score (DIAAS). The results showed that there is considerable variation in DIAAS within the same protein source and among different protein sources. Among the selected protein sources, pork meat, casein, egg, and potato proteins are classified as excellent quality proteins with an average DIAAS above 100. Whey and soy proteins are classified as high-quality protein with an average DIAAS ≥ 75 . Gelatin, rapeseed, lupin, canola, hemp, fava bean, oat, pea, and rice proteins are classified in the no quality claim category (DIAAS < 75). Therefore, the paper provides information on the quality of different plant and animal-based proteins based on their amino acid profile. These factors are particularly important for meat analogues because they intend to replace animal meat which is a potent source of rich quality protein.

Due to differences in composition and structure, plant-based meat analogues seem to have gastrointestinal destinies distinct from actual meat products. Designers have used INFOGEST to test in-vitro metabolism prototypes to make comparisons of the gastro-intestinal outcome of soy-based beef mince analogues, concentrating on distinctions in morphology, physiochemical, lipid and protein digestive health in various regions of the prototype intestines (Zhou *et al.*, 2021). The study concluded that the addition of dietary fibres in beef analogues improved their observable shear viscosity in gastrointestinal fluids, possibly inhibiting lipid digestion inside the small intestine. The proteins in

the beef analogues digested faster in the stomach but slower in the small intestine, which could be attributed to differences in protein form (globular soy and fibrous beef proteins), structure and the presence of dietary fibres in the meat analogues.

In some cases, plant fibres used in the formulation have been shown to suppress lipid digestion due to their capacity to decrease the accessibility of lipase to lipid droplet surface or by promoting droplet flocculation or interacting with chemicals such as bile salts and free fatty acids (Espinal-Ruiz *et al.*, 2014).

Market potential

The rapid market growth of meat analogues is fueled by consumers' growing desire for healthier and more sustainable alternatives to meat, which has led to the entry of major meat manufacturers into the meat replacer category. The global market for meat analogues is estimated to be worth USD 1.88 billion in 2022. It is forecasted to grow with a compound annual growth rate (CAGR) of 14.3% and reach USD 4.04 billion by 2027 (Meat-substitutes market, MarketsandMarkets). Initiatives from the industry are aimed to lower the manufacturing costs of meat analogues, while processed meat manufacturers are introducing vegetarian versions of their meat products. The lowering of cost achieved by mass production can make the product affordable to people of all economic classes. Being a sustainable protein source, there is greater scope for such products to have tax exemptions or reductions with the support of the government in overcoming malnutrition issues like marasmus and kwashiorkor. According to market research, there are possibilities inside the fast-expanding product category of meat substitutes if they highlight selling points like 'well-being', 'comfort', and 'affordability' (Schreuders *et al.*, 2021).

Continuous innovation has led to the launch of 500 plus meat analogues products in India between 2021 and 2022. The launched innovative meat substitutes dominated the newly launched products in other categories like processed meat, poultry, fish and egg products (Mintel market insights).

Positioning claims and their scientific basis

The top 10 positioning claims (marketing) used for meat-substitute products launched between 2021 and 2022 in India are depicted in Figure 1. All these stated claims of meat analogues are supported

by research findings. It can be seen that all the products (100%) used vegetarian claims for promoting their product. It is followed by the second highest claim (55.5%) - plant-based. These two product claims could aim at people who do a slow and steady transition from a non-vegetarian to a vegetarian. Also, these claims help to clearly distinguish the prime characteristics of meat analogues from other products on market shelves. The high/added proteins claim targeting the health-conscious people and muscle-building sports persons constitutes 41.2%. When animal meats contain 20 to 30% protein content, the meat analogues exhibit added protein value as they are usually made from legumes like soy and other algal sources which have 40 to 60% protein. Unlike animal meat which takes a longer time for digestion and net protein utilization of fibrillar proteins in it is low, the absorption rate of globular plant proteins in plant-based meat analogue is high due to its low molecular weight and better water solubility (Zhou *et al.*, 2021). Thus, it is true that meat analogues exhibit higher protein quantity as well as quality. The other less commonly used claims like no additives/preservatives, low/no/reduced cholesterol, environmentally friendly product, free from added/artificial preservatives, and vegan/no animal ingredients do not differ significantly. These claims are also associated with other ingredients used in the formulation of meat analogues. It is well established that no plant-based ingredients in nature have cholesterol but animal meat does have a high amount of cholesterol and saturated fats. As fresh animal meat contain very high water activity, it is highly susceptible to microbial spoilage and so preservatives/additives are needed to extend the shelf life. However, the extruded and dried meat analogue contains low water activity and so preservatives are not very demanding. These claims mainly focus on environmentally conscious consumers who want the products to be more natural, organic, and manufactured without leaving a carbon footprint. The ease of use is the least used claim because it not always meat analogues come in ready-to-eat or instant cooking formats. The positioning claims of the products which are not only vegan but also do not contain dairy ingredients such as casein are found to be 31.75% (Mintel market insights). Consumers who are allergic to dairy proteins can find this claim most important and appealing.

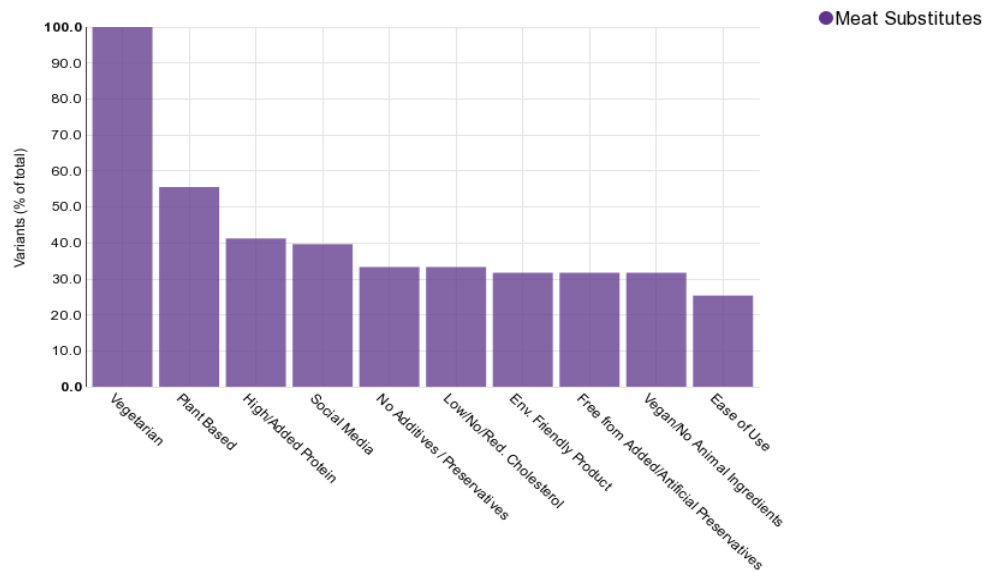


Figure 1. Positioning claims used for different meat substitute variants launched in the period 2021-2022 (Mintel market insights)

Challenges & constraints in the industry

The most important part of developing a meat analogue is trying to recreate the sensory quality of meat with components of vegetables. Even so, utilizing numerous processing methods such as extrusion, shearing, and, to a smaller extent, spinning, plant-based ingredients can be used to mimic the original meat. The development of meat analogue solely from one particular legume is not desirable as it may not meet the daily essential amino acids requirement. However, when the proteins of different plant sources are combined, this problem can be addressed. Unlike animal products, plant-based products contain many anti-nutritional factors like trypsin inhibitors that can suppress the digestibility and bioavailability of proteins. This can be overcome by heat-induced denaturation or selective membrane filtration techniques. Legumes naturally have a beany off-flavour (Egbert and Borders, 2006). This has been the main reason why consumers reject soy milk in the market. Masking or reduction of off-flavour components from ingredients is possible by precise-temperature controlled flavour profiling. A volatile sulfur compound-rich flavour extract giving meaty and spicy flavours can dominate and mask the endogenous beany flavours (Bhuva *et al.*, 2021). Aside from taste, appearance has a significantly greater impact. Heat-stable colouring agents may play a significant role because the meat analogue should not become dull and unattractive upon application of frying, roasting, or other heating

techniques. The next challenge is the integrated texture and mouth feel of meat analogue during eating. Juiciness and tenderness are desired attributes in meat analogues. The time needed for chewing and mastication before the bolus is ready for swallowing should neither be too low nor too high. Although more flavours can be released from the food matrix if longer chewing time, it would drain the energy of the consumer soon. The optimum mouthfeel can be created by modifying the water retention capacity of ingredients and giving a lubricating feel with the addition of fats and oils (Kyriakopoulou *et al.*, 2021).

Even these supplemental ingredients added to overcome the constraints influence the overall nutritional quality and flavour profile of the meat analogue (Rackis *et al.*, 1979). The fats and oil depending on the degree of unsaturation undergo oxidation and hydrolysis during the heating and storage of meat analogue. It is also quite a challenge to have a homogenous product in which hydrophilic and lipophilic ingredients co-exist. The addition of fats means the nutrient density (Kcal) of the product will increase. This goes against the consumer's long-standing preference for fat-less healthy products. Even if these fats added into meat analogues are replaced with protein/carbohydrate gel-based fat substitutes, whether these fat substitutes give a desired melting sensation and juiciness in the mouth is a question mark as both protein and carbohydrates have melting temperatures extremely higher than the human body temperature (Basediya

et al., 2013; Malav *et al.*, 2015). A change in water retention capacity to have the desired mouth feel means water activity in food is also influenced. This can promote microbial growth in a product under supportive conditions prevailing in storage.

Of all foods, animal meat is the richest source of iron. It is commonly prescribed by medical practitioners for people suffering from anemia. If plant-based meat is to be produced, it should not only focus on proteins but also other micronutrients like vitamins and minerals. Although plant sources do contain iron, the quantity is still not high enough. This can be addressed by the fortification of plant-based meat. It is to be realized that fortification would increase the price of the product. Verbeke *et al.* (2010) stated that the customer preference in Europe for pork and beef mainly focused on iron. Moreover, iron in animal meat exists as a part of the complex porphyrin ring structure of hemoglobin and myoglobin in muscles. Iron bound to myoglobin will not catalyze the oxidation of fats in the fatty tissue of animal meat. In plant-based meat, the fortification of iron would significantly cause oxidation of fat ingredients used in the product. This can be overcome by the co-addition of synthetic chelating or sequestering agents like EDTA. The addition of synthetic EDTA again goes against the consumer's demand for a product with only natural ingredients (additive-free). However, no permitted natural chelating agents (i.e. citric acid) are as effective as synthetic ones (Franca *et al.*, 2022).

Furthermore, the plant-based meat analogues market can support carbon footprint labels that demonstrate the products' sustainability; labels that the meat industry is still hesitant to use. The added ingredients which are either chemically synthesized or extracted from natural resources through numerous industrial processing steps have sparked debate among environmentally conscious consumers about whether market-existing meat analogues are really green foods (Röös *et al.*, 2014). The variation in the setting temperature of plant and animal proteins poses another challenge. Depending on the extent of cooking, the texture of animal meat differs i.e. rare, medium-rare, well-done etc. The consumers for whom cooking animal meat is not uncommon may expect specific textures in plant-based meat if cooked with similar time-temperature combinations. However, as the denaturation temperature of plant and animal proteins are not the same, this variation in setting temperature gives unexpected and sometimes bad texture profiles to cooked meat analogues. This can be overcome by blending different plant proteins as well as other ingredients at a ratio that exactly mimics the cooking properties of animal meat. But this is very hard to establish. As the partial hydrolysis of

proteins and changing the pH and water activity can influence the denaturation temperature, their optimization could be a solution (Curtain and Grafenauer, 2019). Otherwise, a simple, feasible and relatively cheaper solution could be providing proper instructions for use in the packaging label of meat analogue. It is a misconception that natural foods are always safe. Even plant sources do contain some toxic components (i.e. cyanide, heavy metals etc.) and anti-nutrients whose levels vary depending on the species, soil, climate, pesticide use, and other biotic and abiotic factors. Also, legumes are highly prone to contamination from fungi producing deadly mycotoxins. If plant-based meat is to be produced, these factors should also be taken into consideration. The trace levels of toxicants in the product must be checked regularly and adequate purification and disinfection steps are to be taken wherever necessary. The adoption and implementation of Hazard Analysis and Critical Control Points (HACCP), risk assessment strategies, good manufacturing practices, and food quality management policies with continuous support from higher-level management can improve both the safety and quality of meat analogues produced in industries (Aldred *et al.*, 2004).

The existing technologies to develop high-quality fibrous plant-based meat are expensive and some are even time-consuming and may not give high daily production output. The simple extrusion technology most commonly used these days in industries does not produce meat analogues having stacked individual layers of protein fibres; it gives a plain continuous matrix of protein. Although these extruded plant-based products in the market are claimed as meat analogues, they don't have typical fibrous meat structures. Plant-based meat produced on in lab scale by shear cell technology has excellent texture just like animal meat but scale-up and industrial production pose even more complications. Mathematical modelling of different variables influencing product quality can help better understand the product (Cornet *et al.*, 2022).

Conclusion

The plant-based meat can effectively meet daily protein requirements of consumers. Vegetables and their derivatives, which are widely acceptable, can be replaced for animal products with no significant deviation in sensory profiles. With right combination of hydrocolloids, structural integrity can be improved and a diverse range of texture profiles can be obtained. Although advanced technologies like electrospinning were known to provide an anisotropic structure similar to animal

meat, the throughput of equipment must be improved for practical purposes. The increased acceptance of proteins of microbial origin as green foods gives an opportunity for the development of new variants of meat analogues like seaweed burgers. With appropriate positioning claims, these innovative products can be aimed at specific target groups. The masking of off-flavour notes in plant-based meat by strong meat flavours, use of fat substitutes, heat-stable colorants and antioxidants, iron fortification, appropriate labelling etc can overcome the current challenges and constraints faced by industries. Moreover these challenges can be overcome by the following solutions with focusing on improving the sensory experience of plant-based meat analogues by enhancing flavor and texture, as well as using sustainable, nutritious, and clean label ingredients. Another possible solution would be exploring the use of microalgae as a promising ingredient for meat analogues production, as they have high protein content and diverse nutraceutical compounds which can increase the nutritional profile and by understanding the physicochemical and structural changes that occur during thermomechanical processing can help in creating meat analogues with desired textural functionality. Furthermore, the emerging technology of 3D printing has the potential to fabricate meat substitutes with intricate structures and reduced material cost and energy. However, challenges such as the lack of food-safe substrates and materials, cost-effectiveness, scalability, and consumer acceptance need to be addressed for the successful implementation of 3D printing in the meat analogues industry.

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