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Exploring sustenance: cereal legume combinations for vegan meat development

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The rapidly increasing global population reached 8 billion in November 2022, which is further projected to reach 9.7 billion by 2050. The question of how to sustainably feed the growing population has become a major concern for many countries. In terms of the global protein supply, animal-based protein sources continue to play a dominant role, particularly in developed countries. However, there is growing interest in plant-based protein sources, particularly in the form of meat analogues, as a way to provide a more sustainable and ethical source of protein. To ensure an adequate supply of protein for the world, it's important to promote sustainable and equitable food systems that provide a variety of nutritious and affordable food options, including both animal and plant-based sources of protein. Additionally, investment in research and development of new plant-based protein sources, as well as new technologies to improve the efficiency and sustainability of animal agriculture, can help to ensure a secure and healthy protein supply for the world's growing population. Cereal and legume combinations play a critical role in the development of meat analogues because they provide an important source of protein that can be used to mimic the taste, texture, and nutritional properties of meat. When combined, cereal and legume products can provide a complete source of protein that is comparable to that found in animal-based products. In terms of developing meat analogues, cereal and legume combinations can be used to make products such as veggie burgers, meatless meatballs, and other plant-based meat alternatives. These products can be made using a variety of techniques, including grinding, texturizing, and extruding, to create a product that mimics the taste, texture, and nutritional properties of meat. The current article revolves around the theme of the potential of cereal legume combinations, current practices, challenges faced, novel ingredients and technological practices in developing sustainable meat analogues.

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Sustainability spotlight

In a world where the demand for sustainable food options continues to rise, the pressing concern lies in the unsustainable practices associated with conventional meat production. Recognizing the urgency of the matter, this research delves into the development of plant-based meat alternatives, focusing on the synergy of cereal and legume combinations. The sustainable advancement within this work is twofold. Firstly, it offers a viable solution to mitigate the environmental impacts of traditional meat production. By exploring the potential of cereal and legume-based vegan meats, this research paves the way for an eco-friendlier, resource-efficient, and lower-emission protein source. Secondly, it aligns explicitly with the United Nations' Sustainable Development Goals (SDGs), notably Goal 2 (zero hunger) and Goal 13 (climate action).

1. Introduction

For ages, proteins have been a vital constituent of human nutrition involved in innumerable structural and functional attributes of human metabolism. Traditionally, humans have relied on animal-based products especially meat as a primary source of high-quality proteins owing to its availability, organoleptic properties, minimal processing, and lesser concerns for antinutritional factors.[1,2] However, fostering livestock animals for meat production is associated with extensive use of land and water, resulting in increased greenhouse gas emissions, thereby contributing to negative environmental impact.[3,4] Protein supply is nutritionally and environmentally crucial in terms of carbon footprinting; in particular, meat consumption has the highest carbon footprint of 3.3 tons, while the vegan diet has the lowest at less than half of it.[5–7] Besides, there are other prominent challenges related to meat consumption such as high-risk health illnesses and the detrimental impact on terrestrial and aquatic biodiversity. Furthermore, animal-based diets may increase the risk of zoonosis, exposure to veterinary antibiotics, and deadly ailments such as colorectal cancer and cardiovascular disease.[8] The exponential population rise of the world, unforced

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limitations from animal-based products, and the ubiquitous trend of vegan communities led to an increase in the demand for the production of sustainable plant-based foods for mankind with sensorial attributes similar to animal meat.[9] To counter these environmental concerns and alleviate public health concerns, plenty of plant-based sources that are alternatives to conventional meat products are being explored. Such sustainable foods are termed plant-based meat analogues (PBMAs), also known by various other terms such as mock meat, meat replacers, imitation meat, faux meat, meatless

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meat, and mimic animal meat across the globe.[10–12] According to the results of a life cycle assessment, meat analogues have a significantly reduced carbon footprint and can thus provide environmentally lucrative alternatives to animal-derived meat.[13,14] The plant-based diet has displayed several benefits, including lowering obesity, the presence of a high amount of nutritional ingredients such as vitamins, micro- and and macro-elements, blood pressure and cholesterol control, positive psychological outlook towards animal welfare.[9,15,16] Conventional mock meats are produced using extrusion, but other novel techniques have also emerged to produce meat analogues such as the spinning technique, 3D printing, shear cell technology, and freeze structuring technique.[17,18] The widespread use of meat across cuisines in the market holds a strong demand irrespective of the season. Consequently, PBMAs can be potentially exploited among a wide array of recipes across cuisines and diets.[19] Since the past decade, there has been a bustle among the scientific community in investigating the potential vegan sources to mimic meat concerning its organoleptic, texture, and nutritional attributes.

Over time, various sources of cereal and/or legume combinations have been employed in developing PBMAs. Legumes, though rich in protein content lack methionine. Among them, soy has been the predominant legume source of interest in this regard. With its remarkable protein content and amino acid profile, soy has been serving as a potent ingredient in developing PBMAs followed by pea protein.[20,21] Cereal proteins have been under-utilized in making PBMAs due to their incomplete amino acid content with regard to the Recommended Dietary Allowance, such as lysine. One exception among cereal proteins is wheat gluten, which has been used in combination with other protein isolates due to its elastic properties like meat.[22,23] The current article intends to provide a review of the essence, constraints faced by current and novel ingredients, and technological applications in developing meat analogues using cereal legume combinations.

2. Importance of cereal legume combinations

Since time immemorial, the use of cereal legume combinations (CLCs) has been a part of the staple diet, depicting their invaluable significance to the human race.[24] CLCs have been a quintessential part of global nutrition with their wide array of nutrients, especially in economically budding countries such as India where the consumption of nutritious food has often been a challenge.[25] Thus, CLCs have always provided a cheaper nutritive alternative by supplying adequate nutrients to humans.[26] In terms of production, global cereal and legume production have been increasing in recent years, driven by improvements in agricultural technology, increased investment in research and development, and a growing demand for food to meet the needs of a growing global population. In terms of consumption, the trend towards plant-based diets and growing interest in sustainable food options are likely to drive increased demand for cereals and legumes in the future. This, combined with the recognition of the health benefits of these foods, is likely to result in increased production and consumption of these crops in the years to come. The global production of cereal grains for the year 2022 as per the forecast of the Food and Agricultural Organization was 2756 million tonnes and consumption of 2777 million tonnes, respectively.[27] The statistics portray the eminence of the consumption of cereal and legumes worldwide, provoking the research brains to keep their focus on this, in developing newer products and technologies. Cereals such as rice, wheat and its products have been eaten for ages but there is a rapid change in the trend of their consumption with the concept of whole cereal grains, which could potentially provide added nutrients such as dietary fibre and phytochemicals.[28,29] Recently a few underutilized kinds of cereal such as oats and barley have gained interest owing to their health-promoting compounds *viz.* β-glucan.[30,31] The idea of breakfast cereals is a common scenario in every household especially in Western countries, explaining its importance. Conversely, legumes are called poor man's meat and are consumed extravagantly across the globe due to their adequate protein, dietary complex carbohydrates, and B vitamins despite some anti-nutritional concerns.[32,33] Legumes such as green gram, black gram, red gram, green peas, and groundnuts have been consumed extensively by hundreds of millions of the world population.[34,35] Legumes due to the presence of anti-nutritional factors require additional processing steps *viz.* tannins, phytates, and cyanogens, whereas cereals require less complex mechanical processing methods to make them fit for consumption.[36–38] Present-day society is more engrossed in the quality of protein being consumed than its quantity. The quality of protein depends on the digestibility of the protein and amino acid composition and is measured in terms of Protein Digestibility Corrected Amino Acid Score (PDCAAS) and Digestible Indispensable Amino Acid Score (DIAAS).[39–41] It is well known that neither cereals nor legumes are balanced with all nine essential amino acids, with lysine and methionine as their limiting essential amino acids, respectively. Therefore, the imbalance in amino acid patterns can be compensated for by consuming a cereal–legume combination diet.[23] Therefore, CLCs could serve as a potential source to target for the development of various sustainable foods such as meat analogues and the products can be established even more in a sustainable way by the implementation of green processing technologies.

3. Meat analogues based on cereal legume combinations

3.1. Extrusion technology

Extrusion technology has been a go-to technology for the development of meat analogues for decades by the virtue of its robustness, versatility, high scalability, low cost and employment of temperature, pressure, shear force, mixing, shaping, expansion, and cooling along with various physicochemical changes *viz.* denaturation, cross-linking, aggregation, fragmentation, complexation of proteins, denaturation and gelatinization of starch, reduction of anti-nutritional factors, increasing the digestibility and bioavailability of nutrients, and idiosyncratic flavour conferment due to the Maillard reaction.[42–44] Nevertheless, extrusion technology has been in the routine of development of meat analogues particularly based on cereal legume combinations. Extrusion conditions were broadly classified into high-moisture extrusion (>40%) and low-moisture extrusion (<40%), based on the moisture content of the final extruded meat analogue.[45,46] For the past half a decade, various new combinations of cereals and/or legume proteins were assessed for their potential in developing vegan meat using extrusion cooking, *viz.*, oat-pea blend,[47–51] soy-gluten,[52–55] soy-gluten-corn starch,[56–58] pea-gluten,[59,60] pea-soy-gluten,[61–65] soy-green gram-peanut-pea-gluten,[45] rice-soy,[66–68] soy-gluten-whey,[69] faba bean-pea,[70–72] peas-lentils-faba beans,[73,74] pea-chickpea,[75] soy-surimi,[76] and rapeseed-yellow pea.[77] Though possessing innumerable advantages, extrusion technology accounts for some drawbacks such as the degradation of vitamins and acrylamide concerns, thereby necessitating the emergence of novel technologies.

3.2. Other novel advanced methods and technological advancements

Although proactive research is being carried out on extrusion technology for meat analogues, there is a meagre shift in the focus on the development of innovative technologies keeping future needs in the picture. The effectiveness of novel advanced techniques in the development of meat analogues compared to traditional methods like extrusion technology is a multidimensional consideration. Traditional extrusion technology has been overexploited in industry, owing to its effectiveness in creating meat analogues with familiar textures and shapes. Its capability of scaling up to meet the demands of mass production efficiently makes it still the most predominantly used technology for the development of meat analogues. However, the prospects of meat analogues are evolving rapidly, and novel advanced techniques are pushing the boundaries to meet perfection. These techniques, such as micro-compounding and 3D printing, offer an attractive level of customization. They enable fine-tuned control over ingredient distribution at a micro-level, thereby offering innovative textures, flavours, and nutritional profiles that can closely mimic real meat. This is particularly valuable for catering to diverse consumer preferences and dietary requirements. Nevertheless, there are concerns about its employment. The cost of implementing advanced techniques, with their specialized equipment and research requirements, can be discouraging for many manufacturers. Scaling up from lab-scale experiments to commercial production presents challenges related to consistency, efficiency, and cost-effectiveness. The acceptance of novel meat analogues, which may differ in texture and appearance from traditional meat, requires consumer education and adaptation. Moreover, the success of these advanced techniques often relies on the availability of suitable ingredients, which may not be universally accessible. One such emerging technology with the widest research in developing meat analogues is 3D printing. The 3D printing technology involves the layer-by-layer deposition of material based on the consumers' desirability (Fig. 1). One of the most significant advantages of using 3D printing is its customization of appearance such as the shape and fibrous structure, thereby increasing the consumers' acceptability.[78] Other advantages also include efficiency, complex shapes, and sustainability. The technology aligns with sustainability goals by reducing the environmental impact associated with meat production. Though possessing numerous benefits, 3D printing has its limitations such as scalability, cost, and speed. The production of 3D-printed meat analogues is a mammoth task for a larger population, thereby limiting its usage to the laboratory level.[79] 3D printing has been employed in the development of reduced-fat meat analogues from emulsion gels,[80] textured soft hybrid meat analogues,[81] application of additives *viz.* hydrocolloids such as gelatin, alginates,[82–84] methylcellulose,[85] xyloses,[86] transglutaminase,[87] and cocoa butter[88] in improving the physicochemical properties of 3D printed meat analogues, and artificial muscle fibre insertion using coaxial nozzle assisted 3D printing.[89] In another distinctive study, Baik *et al.*[90] incorporated *Gryllus bimaculatus* powder into a soy-based 3D printed analogue. Woo Choi *et al.*[91] developed a novel technology for high moisture texture soy protein using a vacuum packaging and pasteurized heat (vacuum-autoclaving) treatment. The treatment was observed to increase the disulfide bonds, α-helix, and β-sheets, despite decreasing the texturization index and hardness of the product. Krintiras *et al.*[92] employed simple shear and heat in a Couette cell to develop a soy-gluten-based meat analogue and were successful in the development of fibrous anisotropic structures that mimicked meat tissue. The Couette cell consists of two concentric cylinders, typically made of glass or metal. The inner cylinder is solid and stationary, while the outer cylinder is rotatable. The space between these cylinders is filled with the fluid or material under investigation, in this case, a meat analogue mixture. When the outer cylinder is rotated, it imparts a shear force to the fluid between the cylinders. This shear force causes the material to flow in concentric layers, with the innermost layer moving at a lower speed (closer to the stationary inner cylinder) and the outermost layer moving at a higher speed (closer to the rotating outer cylinder). This creates a gradient of shear rates within the material. Like 3D printing, the technique is useful for laboratory-scale research, but scaling up the findings to industrial production can be challenging. Achieving the same texture and properties in large batches may require additional adjustments and considerations. Besides, using the Couette cell requires specialized equipment and expertise, which may not be readily available to all researchers or food manufacturers, thereby limiting its accessibility. Micro-compounding is another recently emerged novel technology, found to be proficient in the texturization of pea protein isolate. The process is more or less similar to the extrusion principle and can be regarded as miniaturized extrusion owing to its usage of a smaller quantity of samples (5–15 ml), which is almost impossible in the case of conventional extrusion, temperature, shear mixing and pressure. One of the strengths of micro-compounding is the ability to customize the ingredient mix. This allows food technologists to fine-tune the texture, flavour, and nutritional profile of the

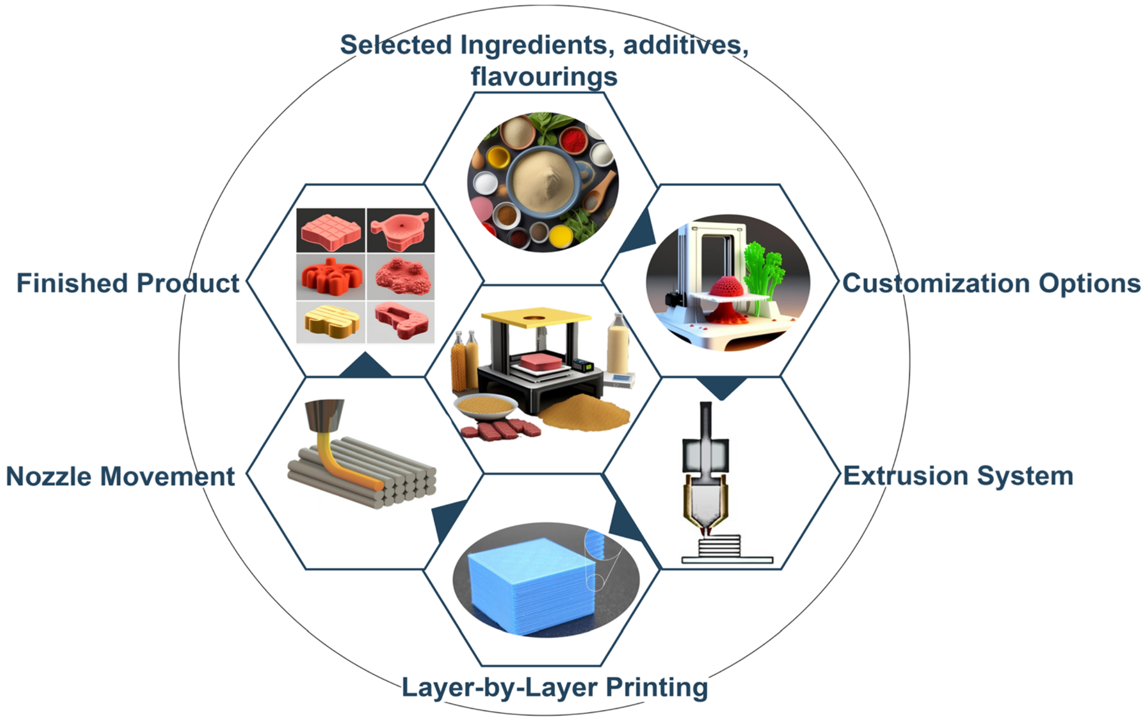

Fig. 1 Salient features and process flow of 3D printing.

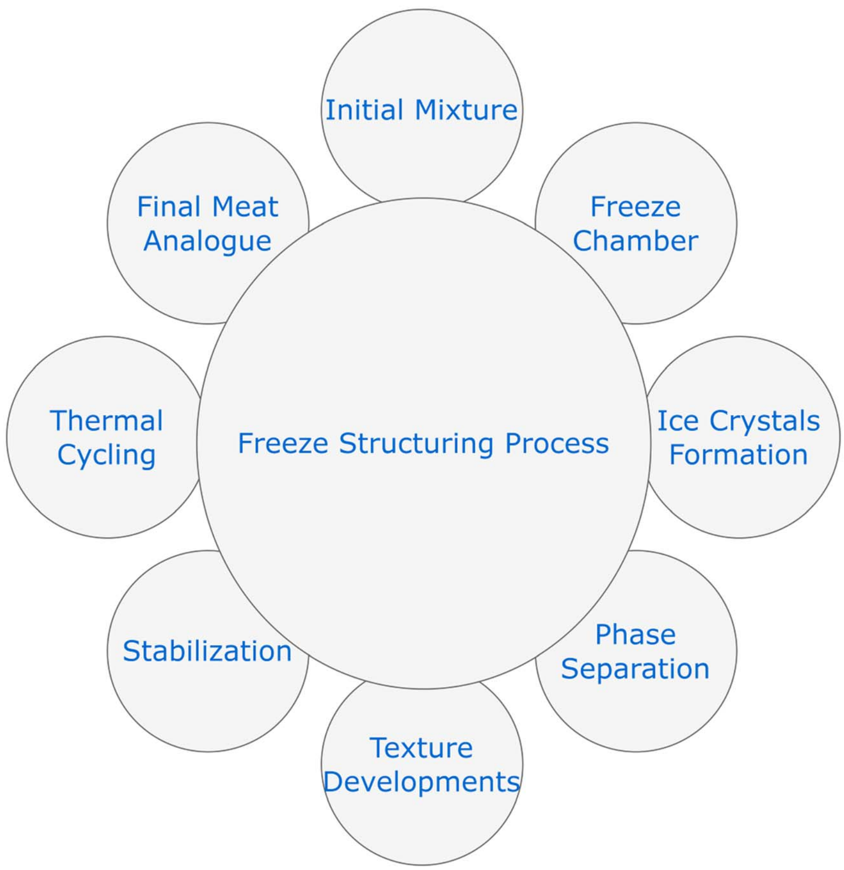

Fig. 2 Various process steps of the freeze structuring technique.

meat analogue to closely resemble real meat. The potential benefits include texture precision, flavour customization, uniformity, and reduced allergenicity. The limitations of the technology include equipment costs, ingredient sourcing, processing time, scalability, and restriction to flavour and taste.[93] Chantanuson *et al.*[94] developed a meat analogue based on soy-protein-based food gels by the freezing technique and evaluated its rheology and fibrous structure. In the freeze-structuring technique, the protein emulsion of the desired source is subjected to freezing to provide a more fibrous structure resembling meat. Furthermore, the ice crystals in the emulsion are removed to leave a more porous and fibrous structure, which mimics the fibrillar protein network of real meat (Fig. 2). Despite exhibiting high yield and product desirability, the technique possesses the same limitations as its co-evolving emerging techniques (Couette cell technique, 3D printing, and micro-compounding) such as scalability, high production cost, slow production rates.[59]

4. Novel ingredients and additive combinations

Human psychology always tends to try out newer sources and look out for a change in the choice of ingredients that are used for the development of any product, which is also applicable in the case of meat analogues.[95] This pushes the scientific community to put extra effort into searching for unexplored commodities. Apart from cereals and/or legume combinations, certain novel ingredients have been explored in developing meat analogues. These include the by-products obtained in the production of other value-added products *viz.* rice bran,[96,97] sunflower meal[98] and rapeseed meal[77] by a conventional extrusion process. This approach reduces the procurement cost of the ingredient and the burden on the industries in the disposal of unnecessary by-products, which could be further exploited for the development of other value-added products. Another emerging commodity in the manufacture of vegan meat is microalgae amidst the speculations that agricultural activities of cereals/legume sources could also play a role in carbon footprinting. Microalgae are one of the noteworthy sources of protein with tremendous protein quality and quantity owing to their immaculate essential amino acid score (EAAI) (>100; the standard value of casein is 100).[99] The EAAI of *Chlorella* sp. and *Arthrospira platensis* is 107.5 and 102.6 respectively, showing them to be a potentially prominent ingredient in this regard.[100] Microalgae also possess an extensive range of pigments with health-benefiting nutraceutical activity, *viz.* β-carotene, astaxanthin, fucoxanthin, and phycocyanin.[101,102] Despite having a resounding protein profile and other bioactive compounds, microalgae have certain constraints, which limit their employment in the development of PBMAs. The production process is energy-intensive and requires the attention of well-trained supervision.[103] The acceptability of microalgae is highly challenging due to its objectionable earthy/fishy odour, which requires prospective technological intervention to make it suitable for consumption.[104,105] Xia *et al.*[106] studied the structural and rheological properties of pea protein-based meat analogues incorporated with *Haematococcus pluvialis* residues using high moisture extrusion. In a similar type of study, soy protein-based meat analogues were extruded with heterotrophically cultivated microalgae called *Auxenochlorella protothecoides*.[107] Jin *et al.*[108] developed a beef jerky analogue using a transglutaminase-treated yuba film, which significantly affected the cross-linking of soy proteins, thereby imparting the soy-based jerky with enhanced cohesiveness, cutting strength and texture. Kim *et al.*[109] developed surimi-based crab meat with a potato starch solution layer analogue using coaxial extrusion 3D printing. Besides the exploration of novel ingredients, there were a plethora of efforts to improve the functional and nutritional properties of existing ingredients with the help of certain additives. Cho and Ryu[110] studied the effect of the addition of mealworm larva (*Tenebrio molitor*) on a physicochemical soy-protein-based extruded meat analogue and observed that the DPPH radical scavenging activity, sulfur amino acid and glutamic acid content of the meat analogue increased with increase in the mealworm composition. Wen *et al.*[86] evaluated the influence of the addition of xyloses on the physical characteristics (colour, texture, rheological, printing properties, and texture) of 3D-printed green gram protein-based meat analogues and witnessed that xylose significantly increased the shear modulus and printing behaviour of the protein gels used for 3D printing extrusion. Palanisamy *et al.*[111] examined the changes in the properties of a soya protein meat analogue added with iota carrageenan and concluded that the additive improved the texturization properties of the meat analogue more than the control. In a similar type of study, Dou *et al.*[112] evaluated the effect of a mixture of gums (iota carrageenan, carboxymethylcellulose sodium and sodium alginate) on the fibre formation properties of a high moisture extruded soy-based meat analogue. Peng *et al.*[113] evaluated the effect of the addition of L-cysteine on the fibrous structure formation of pea protein and witnessed a decrease in fibrous formation when the additive concentration exceeded 0.09%. The influence of oyster mushroom addition on the physicochemical properties of a full fat soy-based analogue extruded burger patty and physical and microstructure properties of low-grade soy proteins, thereby indicating the potential of mushrooms in improving the quality of meat analogues.[114–117] Palanisamy *et al.*[118] included various ratios of spirulina/lupin protein mixtures and observed a significant increase in the properties such as *in vitro* protein digestibility, total phenolic content, and total flavonoid content. Xia *et al.*[119] and Jeon *et al.*[56] incorporated yeast into a soy protein-based meat analogue and concluded that yeast increased the fibrous structure of the products besides making them brighter and whiter. Similarly, Jeon *et al.*[57] evaluated the influence of the addition of brewers' yeast on the quality characteristics of high-moisture extruded meat analogues. Mandliya *et al.*[120] investigated the effect of the addition of mycelium (*Pleurotus eryngii*) in a pea-protein-based low moisture extruded meat analogue on the rehydration, physicochemical and functional properties. Bakhsh *et al.*[121] studied the synergistic effect of lactoferrin and red yeast rice on the physicochemical properties of pea and soy protein-based-meat analogues. Szpicer *et al.*[75] attempted to develop a meat analogue with enhanced antioxidant activity with the addition of micro-encapsulated anthocyanins and optimized the conditions to the inclusion of 2.74% of anthocyanins. Moll *et al.*[122] compared the binding characteristics of a laccase-treated pea-protein-sugar beet pectin mixture with methylcellulose treated in a bacon-type meat analogue.

5. Consumer attitude towards cereal legume based meat analogues

Consumer behaviour towards meat analogues made using cereal legume combinations is influenced by various factors, including health concerns, environmental concerns, personal values and beliefs, and taste preferences.[123] In recent years, there has been a growing trend towards plant-based diets, as consumers become more conscious of the environmental impact of animal-based products and the health benefits of consuming more plant-based foods.[124] This has led to increased interest in meat analogues made using cereal legume combinations, as consumers look for sustainable and healthy alternatives to traditional animal-based products.[125,126] However, taste remains an important factor for many consumers, and some may be hesitant to try meat analogues if they do not believe that the products will taste good.[127] To overcome this, food manufacturers are working to improve the taste and texture of meat analogues, and many have been successful in creating products that are indistinguishable from traditional meat products.[128] Additionally, there are also cultural and personal factors that may influence consumer behaviour towards meat analogues.[129] For example, some consumers may be hesitant to try meat analogues due to a lack of familiarity with these products, while others may be more likely to try them due to personal values and beliefs.[130] In conclusion, consumer behaviour towards meat analogues made using cereal legume combinations is influenced by a complex interplay of factors, including health and environmental concerns, personal values and beliefs, and taste preferences. To ensure that these products are widely adopted, it will be important for food manufacturers to continue to improve the taste and texture of meat analogues, while also educating consumers about the benefits of these products and addressing any misconceptions they may have.

6. Bottlenecks in the development of vegan meat

Though there is fast moving trend in society about the consumption of meat analogues, a wide range of challenges are being faced by researchers and industries from the selection of ingredients, complexity involved in the processing, palatability with the local cuisine, and consumer acceptability. Although cereal and legume combinations possess lots of essential nutritional dimensions, there are a few limitations faced by the researchers in employing this commodity for the development of meat analogues (Fig. 3). Cereals and legumes possess a wide range of anti-nutritional factors, thereby requiring additional processing steps to remove them.[37,131,132] Among legumes, soybeans in the form of soy protein isolates have been widely employed due to their good protein quality and better functional properties followed by pea protein and chickpea protein.[23] Unlike legumes, cereals, except for wheat, do not possess an adequate quantity of protein with the functional properties thus posing additional challenges in their utilization and failing to grab the interest of scientific and corporate communities in developing plant-based meat analogues due to their poor protein functionalities for large scale usage.[133] Currently, soy protein isolates and vital wheat gluten are predominantly used, which are obtained after plenty of processing and purification stages inevitably increasing the production cost. In contrast, the quality of animal meat is relatively too high in comparison, thereby throwing a challenge to the research community to explore the technologies and resources that could match the protein quality of meat

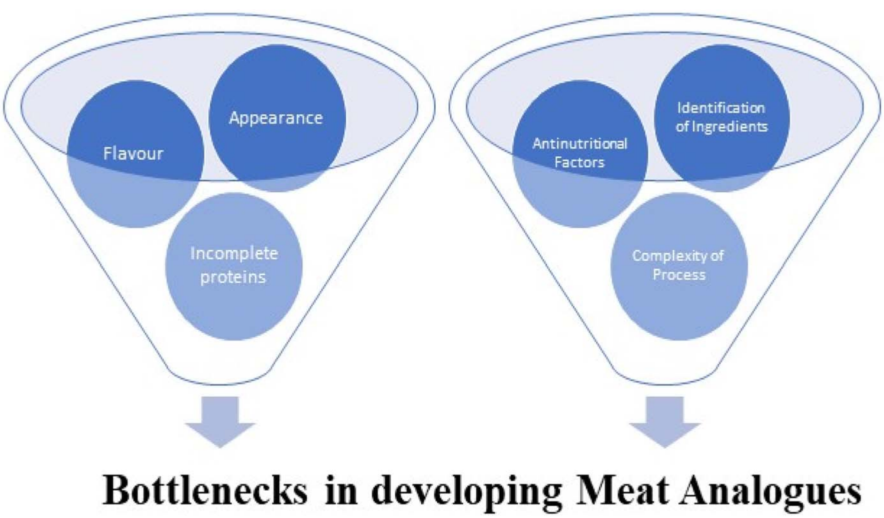

Fig. 3 Challenges encountered during the development of vegan meat.

analogues to conventional meat without increasing the production cost.[134] Besides their exemplary usage, soy and gluten have been two of the most common allergic concerns across the world. Approximately 3–10% of adults and 8% of children suffer from soy allergy and celiac disease worldwide, which shows the need to explore other potent ingredients for the development of vegan meat.[135–137] The identification and procurement of raw materials that have the potential to replace meat tissue and fibre in terms of the texture and nutrition have always been a hurdle because there is not any such single source on this planet that is cheap and mimics meat in its physicochemical and organoleptic attributes.[126] Therefore, an array of ingredients are being used in combination including cereal and legume sources making the preparation and processing stages complex. A commercially available plant-based analogue uses an average of 25–30 ingredients with different moisture contents, particle sizes, flow behaviours and solidity of the ingredient through various automated processes (conveyer and hopper).[138] To ensure uninterrupted production flow, a crucial step called premixing of ingredients is another critical step in this regard. The ingredients involve a lot of soluble and insoluble fractions for meat structure construction, and some of them have to be distributed properly to avoid complications, thereby making the manufacturers look beyond the continuous process.[139] On account of a lot of hurdles, manufacturers are being forced to choose the batch process, which decreases the productivity rate and increases the production cost. Another challenge in developing vegan meat is the consumer's acceptability in considering it as a convincing alternative to meat. Factors such as the appearance, flavour, taste, and texture that make the consumer perceive meat have always been a challenging task.[140] The appearance (colour) is the first one to catch any person's interest in any food.[141] The hurdle in this context is that cereal and legume-based ingredients normally used in the flour form vary from a white to a beige colour, which turns yellowish due to the Maillard reaction when cooking. Meat analogues should mimic conventional meat with red inside and brown outside when cooked.[142] Another hurdle is the development of meat flavour. Cereal and legume origin ingredients range from sweet to beany flavour sometimes owing to the lipoxygenase activity on unsaturated fatty acids making their excess utilization limited.[81] The process of meat flavour induction in the product is more tedious than the other perception factors. This is due to the presence of volatile flavour compounds that are particular to the natural meat tissue.[143] A few compounds can be used in creating typical meat flavours *viz.* glutamates and ribonucleotides that in synchronization with the Maillard reaction develop an idiosyncratic flavour, thereby increasing the chances of consumers' acceptability.[144–146] The processing challenges of meat analogues have been minimal with the advent of twin-screw extruders, where proper mixing and uniform heat distribution have enabled their reliability in developing high-quality meat analogues with greater acceptance rates.

Addressing the complex challenges in developing meat analogues based on cereal and legume combinations requires a multifaceted approach. First, in tackling the presence of anti-nutritional factors in these ingredients, researchers should invest in advanced processing techniques to effectively remove these undesirable components, thereby streamlining the production process. Additionally, the issue of low protein content in cereals can be mitigated by combining them with legumes, creating a balanced protein profile for meat analogues. Research into isolating and enhancing the functionality of proteins from less-utilized cereal sources can also yield promising results.

The cost of production and quality comparison with animal meat pose significant hurdles. To address this, it's crucial to invest in ongoing research to discover cost-effective and sustainable protein sources that can match the quality of animal meat without inflating production costs. Continuous optimization of the production process is essential to strike a balance between quality and affordability. Furthermore, addressing allergic concerns related to soy and gluten necessitates exploration into alternative protein sources that are hypoallergenic and can effectively replace these ingredients. Ingredient complexity can be streamlined by standardizing combinations and investing in automation for ingredient handling and mixing, ensuring consistent product quality.

Consumer acceptance is a pivotal aspect of success in this industry. Achieving the desired appearance, flavour, and texture is crucial. Natural colourants can be utilized to mimic the appearance of conventional meat. Extensive research into flavour development using compounds like glutamates and ribonucleotides, in tandem with the Maillard reaction, can create distinctive meat-like flavours. Texture improvement through ingredient selection and process refinement is an ongoing endeavour.

7. Carbon footprint of vegan foods and adoption of green processing

Greenhouse gas (GHG) emission has been a human concern for decades contributing to global warming and an increase in sea level causing a threat to seashore areas in the near future. Food products right from the stages of their manufacture (growing, farming, and processing), transport, storage, consumption, and wastage have been inevitable stakeholders in deteriorating environmental health.[147] Recently, there has been an inclusion of another term called carbon footprinting, which gives a clear indication of what scale of the effect of food products' impact on global environmental concerns can be measured.[148] The carbon footprint is defined as activity pertaining to any individual, organization, product, or commodity that plays a role in releasing and accumulating carbon dioxide into the atmosphere.[149,150] At present, the food supply chain holds a moderate stake of 30% of global carbon emissions (13.87 billion metric tons of carbon dioxide equivalents per annum) by human actions, which is expected to increase further with the increase of the world population and food requirements.[27] Nevertheless, it is a two-way entanglement with the negative impact of climatic change on food supply causing massive agricultural loss.[151] The recent trend of veganism gaining pace with the

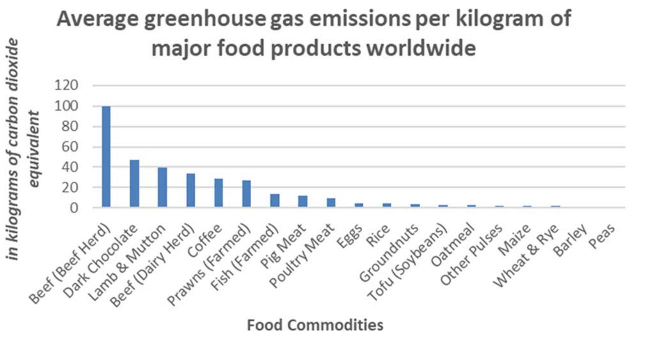

Fig. 4 Carbon footprint comparison of meat with cereal and legumes (source: food product GHG emissions per kilogram worldwide[153]).

concept of being sustainable intrigues researchers in developing foods having smaller carbon footprinting making the food supply chain sustainable. Sustainability is a complicated term, which addresses the requirements of the existing generation without putting future generations at stake to meet their needs.[152] Among the global GHG emissions of food products (per kilogram of food product), 5 out of the top 10 highest contributors belong to meat commodities (Fig. 4), with beef meat (beef herd) (99 kg CO_2e) and lamb and mutton (39 kg CO_2e) ranking first and third, respectively, indicating how crucial their contribution is to carbon footprinting. In contrast, cereals and legumes account for less than 4.5 kg CO_2e, thereby making them a potential source in developing novel products by providing similar characteristics to meat in terms of nutrition and organoleptic attributes.[153] Though it is slightly easier to opt for sustainable dietary habits among individuals seeking change in lifestyle preferences, it is quite unrealistic to expect a drastic shift in the dietary pattern of a large set of the population, especially where meat has been a part of the traditional cuisine.[154,155] As mentioned before, apart from food consumption, food processing also extends a significant amount of contribution to global carbon footprinting.

Therefore, the adoption of green processing could make the current worsening condition slightly better. Earlier, food processing was all about maintaining food safety, complying with regulatory stipulations, meeting consumer requirements, and profitability, whereas environmentally friendly practices have always been the least thing to bother about.[156] Nowadays stringent compliance regulations from food safety and environment protection agencies make processing sustainability-oriented rather than profit-oriented.[157] Green food processing technologies make use of minimal water and energy usage, providing high-quality products that are safe for disposal to the environment. Emerging green technologies include high hydrostatic pressure processing, pulsed electric field processing, plasma processing, the controlled pressure drop process, and supercritical fluid extraction.[158,159] Thus food industries must step forward in choosing ingredients of a lower environmental impact without compromising nutrition and adopting green processing techniques for the development of vegan meat that could reduce the burden on the environment.

8. Missing links in the development of sustainable meat analogues

Developing sustainable meat analogues is an exciting area of research, but there are still some important research gaps and missing links that need to be addressed. One of the biggest challenges is achieving the right texture, as plant-based proteins often lack the fibrous texture of meat. Additionally, while plant-based proteins are often rich in protein, fibre, and micronutrients, they may not contain all of the essential amino acids found in meat, requiring more research to optimize the nutritional profile of meat analogues. The flavour is also a challenge, as meat analogues often lack the complex flavour profile of the meat. Cost is another issue, as sustainable meat analogues can be more expensive than conventional meat, which can limit their accessibility and adoption. Finally, despite growing interest in sustainable meat analogues, consumer acceptance remains a challenge, and more research is needed to understand consumer preferences and develop strategies for increasing consumer adoption. While interest in plant-based and sustainable foods is growing, consumers still have certain expectations around taste, texture, and nutritional value that need to be met. Researchers need to understand these preferences and develop strategies for improving the consumer acceptance of sustainable meat analogues, such as using marketing and education to increase the awareness of the benefits of these products and partnering with chefs and food companies to develop appealing and innovative product offerings. Addressing these research gaps and missing links will require continued investment in research and development, collaboration between industry and academia, and a focus on creating products that are not only sustainable but also appealing to consumers.

9. Conclusion and future prospects

The demand for sustainable foods calls for the exploration of every potential resource either in terms of ingredients or technologies leaving no stone unturned. The trend is driven by consumers seeking a healthy lifestyle change besides concerns about environmental issues. Meat analogues made up of cereal–legume combinations are cost-effective protein sources with negligible portions of saturated fat and cholesterol, providing health-benefiting compounds such as dietary fibres and phytochemicals. Nonetheless, the availability of meat analogues in the market is very scarce when compared with the market of meat products. The market prospects of meat analogues also require improvement owing to the consumer's attachment to conventional meat. It is difficult to know the key reason affecting the increase in consumption of meat analogues over meat. It is believed that the choice of ingredients plays a very crucial role in the consumer's acceptability. The marketing of a meat analogue has always been a tough job for food entrepreneurs due to the inclusion of the term meat. There were quite a few appeals to impose a ban on the use of the term "meat" in developing meat analogues, which is felt to be deceptive by some, but the European Parliament in the early 2020s ruled this plea in favour of the usage. There is a clear communication and research gap in knowing the requirements of meat analogues that the consumer is expecting apart from being a good protein source. The consumer is more likely to anticipate the extra added nutritional benefits *viz.* dietary fibre, fat-soluble vitamins as in meat, and phytochemicals.

In conclusion, the use of cereal and legume combinations for the development of sustainable meat analogues is a promising area for the future of food production. By combining these plant-based ingredients, it is possible to create products that mimic the taste, texture, and nutritional properties of meat, while providing a more sustainable and ethical alternative to traditional animal-based products.

Looking ahead, there is a significant opportunity for continued research and development in this area, including the development of new and improved plant-based protein sources, as well as the use of innovative processing techniques to improve the taste and texture of meat analogues. Additionally, as consumer demand for sustainable and ethical food options continues to grow, there is a clear need for continued investment in the development of meat analogues as a key part of a more sustainable and equitable food system.

To ensure the success of this field, it will be important to work closely with farmers, processors, and food manufacturers to ensure that plant-based protein sources are produced in a way that is both environmentally sustainable and economically viable. Additionally, collaboration with government, industry, and academic partners will be key to advancing the science and technology of meat analogue production and ensuring that these products are widely available and affordable for consumers.

In summary, the future of sustainable meat analogues made using cereal and legume combinations is bright, and there is great potential for continued innovation and growth in this field. By working together to create products that are delicious, nutritious, and environmentally friendly, it is possible to help build a more sustainable and equitable food system for future generations to make the world a better place to live.

Author contributions

Mr Kannan Vignesh: preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation), ideas and formulation or evolution of overarching research goals and aims. Mr Dev Kumar Yadav: supervision of the planned work including review and commentary of the manuscript. Dr D. D. Wadikar: planning, guidance and assigning responsibility to the research activity. Dr A. D. Semwal: management and coordination responsibility of the research activity.

Conflicts of interest

There are no conflicts to declare.

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