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A Review of Alternative Proteins For Vegan Diets: Sources, Physico-Chemical Properties, Nutritional Equivalency, and Consumer Acceptance

Rutwick Surya Ulhas
Friedrich Schiller University, Germany

Rajeev Ravindran
Munster Technology, Tralee, Ireland

Alok Malviya
CHRIST (Deemed-to-Be University), Bangalore, India

See next page for additional authors

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Authors

Rutwick Surya Ulhas, Rajeev Ravindran, Alok Malviya, Anushree Priyadarshini, Brijesh K. Tiwari, and Gaurav Rajauria

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A review of alternative proteins for vegan diets: Sources, physico-chemical properties, nutritional equivalency, and consumer acceptance

Rutwick Surya Ulhas[a], Rajeev Ravindran[b], Alok Malaviya[c,d,*], Anushree Priyadarshini[e], Brijesh K. Tiwari[f], Gaurav Rajauria[b,g,h,*]

[a] Faculty of Biological Sciences, Friedrich Schiller University, Jena, Germany
[b] Circular Bioeconomy Research Group, Shannon Applied Biotechnology Centre, Munster Technology, Tralee, Ireland
[c] Applied and Industrial Biotechnology Laboratory, Department of Life Sciences, CHRIST (Deemed-to-Be University), Bangalore, Karnataka, India
[d] QuaLife Biotech Private Limited, Hosur Road, Bangalore, Karnataka, India
[e] Environmental Sustainability & Health Institute, Technological University Dublin, Dublin, Ireland
[f] Department of Food Chemistry and Technology, Teagasc Food Research Centre, Ashtown, Dublin, Ireland
[g] School of Microbiology, School of Food and Nutritional Sciences, University College Cork, Cork, Ireland
[h] SUSFERM Centre for Sustainable Fermentation and Bioprocessing Systems for Food and the Bioeconomy, University College Cork, Cork, Ireland

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ABSTRACT

Alternate proteins are gaining popularity as a more sustainable and environmentally friendly alternative to animal-based proteins. These proteins are often considered healthier and are suitable for people following a vegetarian or vegan diet. Alternative proteins can be recovered from natural sources like legumes, grains, nuts, and seeds, while single cell proteins (mycoproteins), and algal proteins are being developed using cutting-edge technology to grow fungus, yeast and algal cells in a controlled environment, creating a more sustainable source of protein. Although, the demand for alternative protein products is increasing, there still happens to be a large gap in use among the general consumers mainly stemming from its lower bioavailability, lack of nutritional equivalency and reduced digestibility compared to animal proteins. The focus of the review is to emphasize on various sources and technologies for recovering alternative proteins for vegan diets. The review discusses physicochemical properties of alternative proteins and emphasise on the role of various processing technologies that can change the digestibility and bioavailability of these proteins. It further accentuates the nutritional equivalency and environmental sustainability of alternative protein against the conventional proteins from animals. The food laws surrounding alternative proteins as well as the commercial potential and consumer acceptance of alternative protein products are also highlighted. Finally, key challenges to improve the consumer acceptability and market value of plant-based proteins would be in achieving nutrient equivalency and enhance bioavailability and digestibility while maintaining the same physicochemical properties, taste, texture, as animal proteins, has also been highlighted.

1. Introduction

The world population is rising at a steady rate. The recent UN projection estimated a population of 8.4 billion to 8.7 billion individuals by 2030 and this would further reach up to 10.2 billion by 2050 (United Nations, World population prospects 2017). Improvements in health care and life expectancy has led to a global increase in the age of the population, and in such a rising and ageing population the protein demand is especially high for an optimal muscle strength and mass (Partridge et al., 2018). However, the climate change has only declined sustainable protein production over the past decades and this vicious cycle of higher food demand and lower production, or quality imminently calls for a novel and sustainable alternative approach. Innovation and interest in both novel protein sources such as plant, algae, and

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* Corresponding authors at: Applied and Industrial Biotechnology Laboratory, Department of Life Sciences, CHRIST (Deemed-to-Be University), Bangalore, Karnataka, India (A.M.); and SUSFERM Centre for Sustainable Fermentation and Bioprocessing Systems for Food and the Bioeconomy, University College Cork, Cork, Ireland (G.R.).

E-mail addresses: rutwick.surya.ulhas@uni-jena.de (R. Surya Ulhas), rajeev.ravindran@mtu.ie (R. Ravindran), alokkumar.malaviya@christuniversity.in (A. Malaviya), anushree.priyadarshini@tudublin.ie (A. Priyadarshini), brijesh.tiwari@teagasc.ie (B.K. Tiwari), grajauria@ucc.ie (G. Rajauria).

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mycoprotein, and their respective processing technologies have been rising steeply (Oonincx et al., 2010; Rolland et al., 2020; Van Huis & Oonincx, 2017). Transition of diet from conventional animal-based protein to alternative protein sources has already shown a better sustainability in health, environment and food security (Cifelli et al., 2016; Hartmann & Siegrist, 2017). Novel processing technologies have shown a potential value addition in the physical, sensory and nutritional architecture of food as well as financial viability of the process (Osimani et al., 2018; Hoehnel et al., 2019).

The alternative protein market is rapidly growing, as consumers are becoming more conscious of the impact of their food choices on the environment, animal welfare, and their health (Siddiqui et al., 2022). As more and more people are moving towards a plant-based lifestyle, alternative protein sources have become a popular topic of discussion. Some common alternative protein sources for vegan diets include legumes (lentils, chickpeas, peas, and beans), grains (quinoa, barley, and bulgur wheat), nuts and seeds (almonds, chia seeds, and pumpkin seeds), mycoprotein (single cell protein from fungus) and algal proteins (Kaur et al., 2021; Zeng et al., 2022; Qin et al., 2022).

While assessing the nutritional equivalency, physico-chemical properties, and environmental sustainability, alternative protein sources have some advantages and disadvantages. The nutritional quality of some alternative proteins can vary considerably, depending on digestibility, structure, function (allergenicity and immunoreactivity), and the availability of essential amino acids (Zeng et al., 2022). Animal-based proteins such as dairy, meat, poultry, and eggs are considered complete proteins because they contain all of the essential amino acids in sufficient amounts. Alternative proteins, on the other hand, are often considered incomplete proteins because they may lack one or more of the essential amino acids (Gorissen et al., 2018). For example, legumes such as beans, lentils, and chickpeas are high in lysine, while grains such as rice and quinoa are high in methionine and cysteine (Hertzler et al., 2020). Therefore, by combining these different plant-based proteins, an individual can obtain a complete protein source that provides all of the essential amino acids needed for optimal health (Gorissen et al., 2018). Additionally, health risks associated with high levels of saturated fat and cholesterol that are contained in animal-derived protein sources, can be avoided by sustaining on plant-based protein sources (Gastaldello et al., 2022). The functional properties of plant protein ingredients depend on the source of the protein and the extraction and processing methods used. For example, soy protein concentrate is typically less soluble than soy protein isolate, making it less suitable for applications in which solubility is important, such as protein drinks (O′ Flynn et al., 2021). On the other hand, soy protein isolate has a neutral flavour and is highly soluble, making it suitable for use in a variety of food products, such as protein bars, bakery products, and snacks (O′ Flynn et al., 2021; Qin et al., 2022). Additionally, the way the protein ingredients are processed can also affect their functional properties, such as their ability to bind with other ingredients, their water-holding capacity, and their ability to form gels (Kyriakopoulou et al., 2021). It's important to consider these functional properties when selecting plant protein ingredients for specific food applications. Considering the environmental sustainability, the benefits of alternative proteins include a reduced environmental impact, as plant-based agriculture requires less water, land, and energy compared to animal agriculture (Bryant, 2022) and cellular agriculture. Additionally, it offers an advantage to reduce greenhouse gas emissions, land use, and the risk of diseases spreading from animals to humans (Li, 2020; Rubio et al., 2020). However, the environmental sustainability of plant-based protein sources depends on various factors, including the type of crop used, the method of farming, and the processing technologies used (Tuomisto, 2019). Therefore, in this paper, recent literature on alternative protein sources and substrates and their respective processing technology are reviewed. The review discusses physicochemical properties of alternative proteins and emphasise on the role of various processing technologies that can change the digestibility and bioavailability these proteins. It further accentuates the nutritional equivalency and environmental sustainability of alternative protein against the conventional proteins from animals. The review then discusses the food laws surrounding alternative proteins and explore various aspects related to commercial potential and consumer acceptance of alternative protein products. Finally, key challenges to improve the consumer acceptability and market value of plant-based proteins would be in achieving nutrient equivalency and enhancing bioavailability and digestibility while maintaining the same physicochemical properties, taste and texture has been discussed.

2. Sources for alternative proteins

2.1. *Plant-based proteins*

Plant-based proteins from legumes, whole grains, nuts, and seeds, are a good source of essential amino acids. Plant-based proteins, such as soy, peas, and grains, are now being used in various food products, such as burgers, sausages, and meat alternatives, creating a more sustainable and ethical source of protein. Plant-based meat alternatives have commonly been based on products derived from soy due to its high protein content (Cober et al., 2022). Soy has traditionally been part of diets in many cultures across the world; in Asia, two soy-based food products *viz.* tofu and tempeh has been staple diets in households for centuries (Djaafar et al., 2010). Although meat-like products can be developed from soy protein alone, the majority of literature point towards the addition of other plant-based materials for improved functional properties in commercial plant-based meat. The following section

Table 1
Protein content and different functional properties of various alternative proteins (Onyeaka et al., 2022; Senthilkumaran et al., 2022; Siddiqui et al., 2022; Wang et al., 2021; Zeng et al., 2022; Liu et al., 2022).

Protein Type	Protein Source	Protein Content (%)	Functions/Applications
Plant-based proteins	Soybean	40	Gelation, fiber formation, emulsification, coil binding
	Pea	20–25	Fiber formation, gelation, emulsification
	Cowpea	40	Gel formation, emulsification, foaming, thickening
	Zein (corn)	45–50	Solubility, foaming, moisture adsorption
	Faba bean	29	Improve physical and oxidative stability of oil in water emulsions
	Wheat	14	Elasticity, extensibility, fibrous structure
	Sunflower	20–28	Foods and Feeds
	Peanut	38	Foods and Feeds, edible coating
	Sorghum	22	Foods and Feeds
	Mustard	24–35	Foods and Feeds
	Barley	12.5	Foods and Feeds
Single-cell proteins	*Saccaromyces cerevisiae*	45–49	Foaming, emulsion, bulk density
	Candida intermedia FLO23	48	Foods and Feeds
	Pleurotus florida	63	Foods and Feeds
	Wickerhamomyces anomalus	56	Foods and Feeds
	Yarrowia lipolytica	48–54	Food application
Algal protein	*Chlorella vulgaris*	51–58	Human Food and Protein Supplements
	Arthrospira maxima	60–71	Human Food and Protein Supplements
	Arthrospira platensis	55–70	Human Food and Protein Supplements
	Euglena gracilis	39–61	Human Food and Protein Supplements

discusses the different components that are used in the formulation of plant-based meat and the technologies used. Table 1. represents the protein content and different functional properties of various alternative proteins.

2.1.1. *Soy protein*

Most plant-based meat alternatives have soy protein as their main component. Its nutritional properties, exceptional gelling properties as well as its ability to fabricate anisotropic fibre structures make soy protein an excellent ingredient for the development of plant-based meat (Hua et al., 2005; Krintiras et al., 2014; Kudełka et al., 2021). Other functional properties of soy proteins include water-holding capacity, fat absorbing and emulsifying capacity (Shih et al., 2016). Soy protein is rich in all the nine amino acids that are necessary for human nutrition (Kudełka et al., 2021). The protein content in soybean meal falls in the range of 44–48 % with the most abundant amino acid being lysine followed threonine, methionine, and cysteine (Panagiota, 2014). However, it lacks sulphur containing amino acids; this can be complemented by other sources of plant proteins that are rich in these amino acids. Furthermore, attempts are being made to incorporate these amino acids into soy proteins via traditional breeding and genetic engineering techniques (Krishnan & Jez, 2018). Defatted soy protein flour, soy protein isolate, and soy protein concentrate are the three main products developed from soy (Zhang et al., 2021). Soy protein has also been employed for the development of formulations. For example, Dong et al. (2023) developed rutin microcapsules by coupling soy protein isolates with chitosan. Rutin is a highly unstable polyphenol with excellent biological activity; the researchers were able to improve the stability of the polyphenol by formulating soybean protein isolate/chitosan hydrochloride-rutin microcapsules which also exhibited a targeted release in intestine in simulated digestion. In another study, pre-emulsified soy protein isolate was found to improve the stability of fermented sausages.

Soy flour and soy protein isolate have been traditionally used for preparing commercial texturized plant-based meat components (Malav et al., 2015). Texturization is an important process in the development of plant-based meat alternatives. The anisotropic fibrous nature of meat contributes to its unique sensory properties which cannot be naturally attained in vegetable proteins. Processing technologies such as high moisture extrusion cooking, electrospinning and shear cell technology are commonly employed to provide texture to vegetable protein products (Baune et al., 2022). Soy-based meat alternatives were developed by Dou et al. (2022) — involving high moisture extrusion technology where the different gums (iota carrageenan, carboxymethylcellulose sodium and sodium alginate) were used as additives. The researchers identified that disulfide bonds followed by hydrogen interactions and hydrophobic interactions contributed to the formation of long extrudates the importance of different chemical bonds between the protein molecules. Electrospinning has also been successfully identified to develop fibrous textures using soy protein isolates (Wongkanya et al., 2017). However, a recent review suggests two strategies *viz.* a top-down approach and a bottom-up approach to develop fibrous plant-based products. While the top-down approach is advantageous from the standpoint of scalability, robustness and resource efficiency, the bottom-up approach provides a plant-based meat product that better resembles actual meat (Dekkers et al., 2018).

2.1.2. *Wheat gluten*

Wheat gluten, commonly known as 'seitan', is used as a binding material that is incorporated with soy to develop plant-based meat. The unique viscoelastic properties of wheat gluten allow it to form a resilient gel making it useful in the preparation of thickeners, fortifiers, and texturing agents (Pietsch et al., 2019). Adding wheat gluten to a soy-based meat formulation can improve the functional as well as nutritional properties of the finalised product as the two plant-based protein materials can supplement their respective amino acid profiles; for example, wheat gluten is devoid of lysine which is found in abundance in soy (Rombouts et al., 2009). The addition of wheat gluten in the extrusion process can improve the hardness and microstructure of the extruded product. Furthermore, wheat gluten can also be used to form meat extenders. The presence of disulphide bonds in soy protein isolate and wheat gluten contribute to the rigid structures resulting in fibre formation in the extrudate. This is primarily determined by the ratio of soy protein and wheat gluten that is subjected to extrusion process (Chiang et al., 2019). Yusuf (2023) conducted a life cycle assessment on the development of vegan bacon using soy protein and seitan. Interestingly, the study reported that seitan-based bacon provided higher protein content to the consumer when compared to regular bacon with a lower fat content. Additionally, the environmental impact of production of seitan-based bacon was much lower as opposed to regular bacon.

2.1.3. *Legume protein*

Legume proteins have also been extensively studied for their potential applications in the development of alternative meat products. Legumes such as chickpea, lentil, pea etc. have been investigated for their several functional properties such as gel formation, emulsification, foam stabilisation etc (Kyriakopoulou et al., 2019). Chickpea is a rich source of dietary protein (17–22 %), has low allergenicity, high solubility and bio-functionality making it an interesting candidate as an alternative ingredient for plant-based meat (Boukid, 2021). In addition to chickpea, pea protein has also drawn interest from researchers as a potential additive in alternative meat products (Lu et al., 2020). The protein content in pea ranges from 14 % to 44 % a majority of which is contributed by albumins and globulins contributing to its high solubility in salt and water (Boukid et al., 2021). Moreno et al. (2020) conducted a study to evaluate the gelling properties of two commercial pea protein isolates to determine their textural properties to develop meat and seafood analogues. They observed that the pea protein isolates were rich in beta pleated sheets imparting properties to form consistent gels. Furthermore, the activity of microbial transglutaminase improved the structural quality of gels in forms from pea protein isolates.

Meanwhile, lentils are nutrient dense pulses with high protein content along with other components such as complex carbohydrates and lipids (Kaale et al., 2022). Arshad et al. (2022) investigated the possibility of developing meat-free nuggets based on lentil protein isolates (LPI) and pea protein isolates (PPI) considering their functional properties, colour, flavour, taste etc. Consequently, nuggets of significant acceptability were developed by maintaining a 40:60 % ratio of LPI and PPI. The study suggested that the colour, appearance, flavour, texture, and taste were satisfactory enough for the novel product to be marketed.

2.1.4. *Other oil seed proteins*

Rape seed meal is a common by-product of oil production using rape seed and is seldom used for food applications. However, this substance is high in protein content (35 %–40 %) and rich in essential amino acids, lysine in particular (Nega, 2018). Furthermore, the presence of cruciferin and napin provides excellent functional properties to rape seed such as emulsification, gelling, oil/water binding properties etc (Shen et al., 2023). However, this seed protein is less preferred over other oil seeds due to the presence of erucic acid which imparts a bitter taste to the final product (Russo et al., 2021). Furthermore, the glucosinolates present in rape seed meal has been found to be detrimental to animal performance (Jhingan et al., 2023).

2.1.5. *Lipids and oils*

The extrusion of plant material that is high in lipid content (<15 %) will result in reduced process efficiency due to reduction in the shear force of the extrusion process and misalignment of molecules (Kyriakopoulou et al., 2019). Therefore, the development of plant-based meat analogues usually involves defatted vegetable proteins (elaborated in earlier sections). This results in the final product being devoid of any fat content. Lipid is an essential additive in the formulation of plant-based meat analogues. The addition of oils to meat alterative products adds flavour while enhancing tenderness while reducing the water holding capacity. Moreover, higher lipid content during the extrusion process can reduce the shear force of the extrusion process. Hsieh and Huff (2012) recommends for not increasing the total lipid content to more than 5 % of the total dry weight of all ingredients.

2.2. *Single-cell protein*

Single cell proteins (SCP) are proteins that are derived from microbial agents such as algae, bacteria, fungi and yeasts. They have similar amounts of lysine, methionine and cysteine content and a higher proportion of threonine and tryptophan content when compared to fish meal (Skrede et al., 1998). SCPs can be used as alternative protein source in animal feeds as well as for human consumption. SCPs have been used an active ingredient in the preparation of crackers, snacks, noodles, soups, baked goods and baby meals. Industrial production of SCP as a source of food protein utilises substances such as methanol, ethanol, cellulose, salts, and whey as carbon source (García-Garibay et al., 2014). A typical SCP production process utilising molasses as the substrate has been provided in Fig. 1. Some of the most common species of bacteria used for SCP production include *Methylococcus capsulatus*, *Methylomonas clara*, *Acinetobacter calcoaceticus*, *Cellulomonas* sp., *Alcaligenes* sp., *Lactobacillus bulgaricus* and *Candida krusei* etc. However, recent studies have investigated the development of single cell proteins by the utilisation of waste streams from agri and food industries (Bertasini et al., 2022). For example, Hülsen et al. (2018) was able to enhance protein content in photosynthetic purple bacteria and five microalgal species while simultaneously removing COD, nitrogen and phosphorus content in industrial wastewater. Additionally, Yang et al. (2017) was able to successfully increase the protein content in photosynthetic bacteria, *Rhodopseudomonas* sp., by 90 % using biogas slurry as substrate. Although, both studies did not involve any feeding trials. However, earlier Wang et al. (2013) conducted a study where the single cell protein obtained from *Corynebacterium ammoniagenes* was used as a protein source in pig feed formulations. The study reported that the standardised and apparent ileal digestibility of the SCP was significantly higher when compared to soy protein. Meanwhile, several yeast species have also been traditionally used for the production of SCPs at industrial scale (Razzaq et al., 2020). Some of the main yeast species used for this purpose include *Candida utilis, Pichia* sp., *Saccharomyces* sp. and *Kluyveromyces marxianus* (Razzaq et al., 2020; Wu et al., 2018). The major algal species that are being exploited to produce SCPs include *Spirulina maxima, Chlorella, Scenedesmus obliquus,* and *Scenedesmus acutus.* Amino acid profile of some of the bacterial and yeast species used to produce SCPs are listed in Table 2.

2.3. *Algal protein*

Microalgae and macroalgae (Seaweed) are traditional food sources in many cultures due to their high protein content and have been used as a source of human nutrition for centuries in some indigenous populations (Nadeeshani et al., 2022; Bleakley & Hayes, 2017; Chakdar et al., 2012). They are increasingly being explored as a promising source of protein and are gaining attention as a viable alternative protein source for vegan or vegetarian diets. Some algal species have comparable or even higher protein content compared to traditional meat, milk, egg, or plant protein sources (Becker, 2007; Boukid & Rosell et al., 2022; Fleurence et al.,

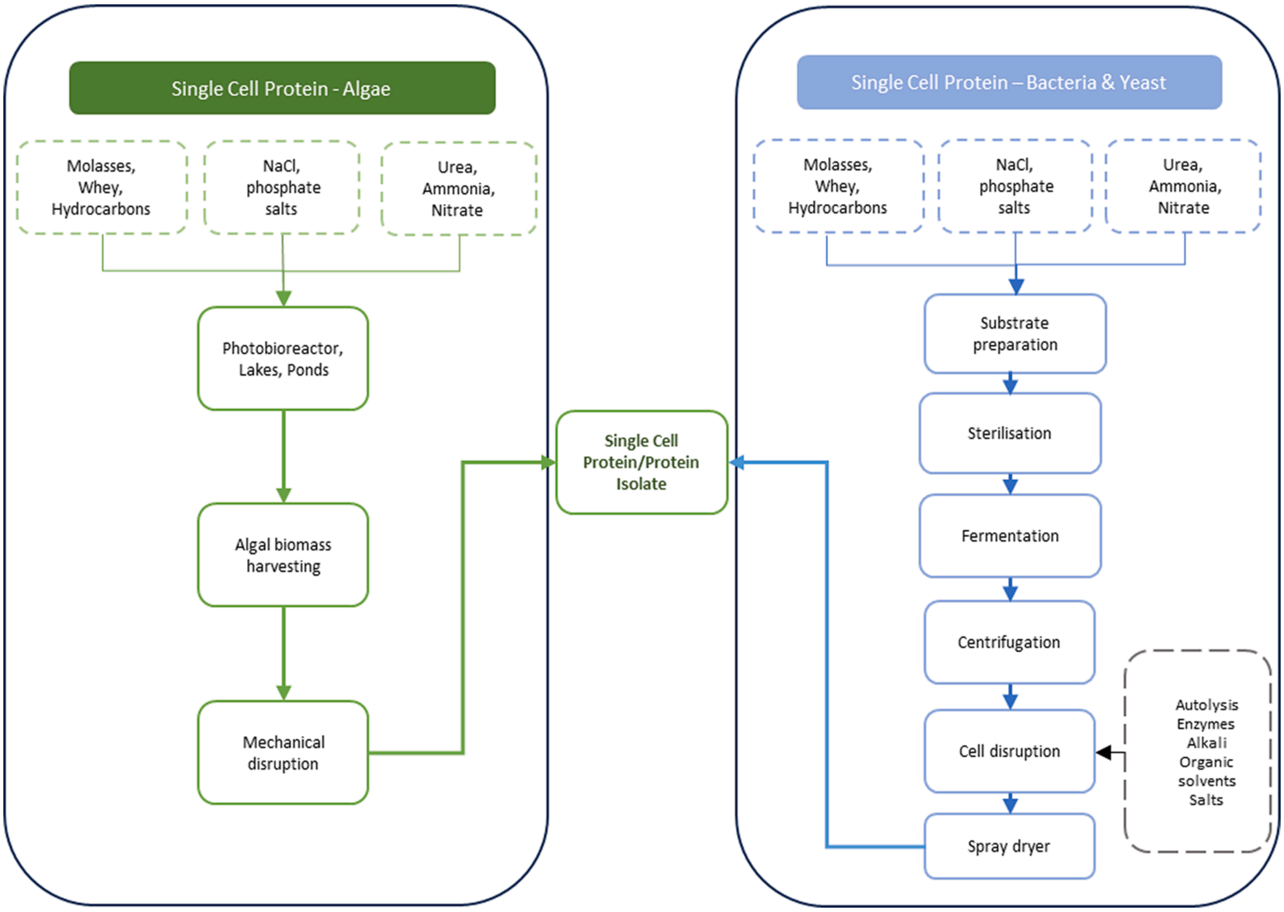

Fig. 1. Flow diagram of single cell protein (SCP) production process from algae, bacteria and yeast (Adopted and modified from García-Garibay et al., 2014 with permission).

Table 2
Amino acid profile of bacterial and yeast species used for the production of single cell proteins. (Adopted from García-Garibay et al., 2014 with permission).

	Kluyveromyces marxianus	*Saccharomyces cerevisiae*	*Candida utilis*	*Methylophilus methylotrophus*	*Methylomonas clara*	*Methylococcus capsulatus*	Soya meal
Protein (g per 100 g dry wt.)							
Crude (N × 6.25)	43–58	48	42–57	72–88	80–85	70–71	44–50
True protein	40–42	36	47	64	69–73	–	48
Essential amino acids (g per 16 g N)							
Isoleucine	4.0–5.1	4.6–5.5	4.3–5.3	5.2–5.4	3.6	3.3	5.4
Leucine	7.0–8.1	7.0–8.1	7.0	8.2–8.4	6.6	5.4	7.7
Phenylalanine	3.4–5.1	4.1–4.5	3.7–4.3	4.3–6.5	5.1	3.2	5.1
Tyrosine	2.5–4.6	4.9	3.3	3.5–3.8	5.1	2.6	2.7
Threonine	4.1–5.8	4.8–5.2	4.7–5.5	5.7–6.5	4.8	3.2	4.0
Tryptophan	0.9–1.7	1.0–1.2	1.2	1.1–1.6	1.5	1.6	1.5
Valine	5.4–5.9	5.3–6.7	5.3–6.3	6.3–6.5	4.8	4.4	5.0
Arginine	4.8–7.4	5.0–5.3	5.4–7.2	4.3–5.6	3.4	4.4	7.7
Histidine	1.9–4.0	3.1–4.0	1.9–2.1	2.2–2.3	2.8	1.8	2.4
Lysine	6.9–11.1	7.7–8.4	6.7–7.2	4.1–7.3	6.2	0.46	6.5
Cystine	1.7–1.9	1.6	0.6–0.7	0.8	–	0.45	1.4
Methionine	1.3–1.6	1.6–2.5	1.0–1.2	1.4–3.0	2.5	1.98	1.4
PER	1.8	2.0	1.7	–	–	–	1.4–2.2
NPU	67	–	–	84	–	–	64
Vitamins (µg/g)							
Thiamin	24–26	104–250	8–9.5	5	–	–	9.0
Riboflavin	36–51	25–80	44–45	40	–	–	3.6
Pyridoxine	14	23–40	79–83	2	–	–	6.8
Nicotinic acid	136–280	300–627	450–550	57	–	–	24.0
Folic acid	6	19–30	4–21	15	–	–	4.1
Pantothenic acid	67	72–86	94–189	11	–	–	21.0
Biotin	2	1	0.4–0.8	3	–	–	–
B_{12}	0.015–0.05	–	0.0001	–	–	–	0

2018; Gouveia et al., 2008). For instance, red seaweed species, such as *Palmaria palmata* (dulse) and *Pyropia tenera* (nori) contain up to 33–47 % protein (Fleurence et al., 2018). Many species of seaweed are particularly rich in amino acids such as aspartic acid and glutamic acid that contribute to the unique taste of seaweed known as “umami” (MacArtain et al., 2007). These two amino acids make up a significant portion of the total amino acids in seaweed species such as Fucus and Ulva, with percentages ranging from 22 % to 44 % and 26 % to 32 %, respectively (Fleurence et al., 2018). The brown seaweed *Laminaria japonica* (kombu) was the source of the flavor enhancer monosodium glutamate that particularly appeals to the umami’ taste sensation (Marcus, 2007). Nevertheless, some essential amino acids are in insufficient supply in algal species. Amino acids such as tryptophan and lysine are commonly limiting in most algal species, while red species of algae have low concentrations of leucine and isoleucine. Similarly, brown algal species have limited amounts of methionine, cysteine, and lysine (Dawczynski et al., 2007; Mišurcová et al., 2014). The essential amino acid (EAA) composition of algae meets the requirements set by the Food and Agriculture Organization (FAO) and are comparable to soybean and egg protein (Machado et al., 2020).

Similarly, microalgal species contain even high levels of protein, with some species such as *Spirulina* and *Chlorella* having up to 63 % and 58 % protein content (dry weight) respectively, which is higher than that of soybeans (approximately 33 %) (Becker, 2007; Bito et al., 2020; Tokuşoglu & Üunal, 2003). These algal proteins can be processed into a variety of food and non-food products, including protein powders, dietary supplements, and even added to functional foods such as noodles, bread, biscuits, drinks, sweets, beer and vegetarian burgers (Pulz & Gross, 2004). Phycocyanin, a blue pigment that belongs to the phycobiliprotein family, is commonly extracted from blue-green algae *Spirulina* sp. The algal pigment is commercially available under the name ‘Lina Blue-A’ in Japan and is used as a food colorant due to its bright blue colour. It is commonly used in a variety of food and beverage products, including chewing gum, soft drinks, dairy products, and the green-coloured hot paste served in sushi bars. In addition to phycocyanin, other phycobiliproteins such as phycoerythrin and phycoerythrocyanin, found in red algae, can also be used as food colorants due to their red and purple colours (Román et al. (2002)).

3. Technologies for developing plant-based meat analogues

As mentioned in earlier sections, technologies that have been developed to produce plant-based meat analogues maybe categorised in to two *viz.* bottom-up and top-down approach to create a fibrous morphology. The bottom-up approach involves assembling individual structural elements to form a larger product. Examples of this type of technique includes wet spinning and electrospinning. Meanwhile, the top-down approach mimics the fibrous structure of meat only on a larger scale. While the structure obtained resembles meat, it does not fully imitate the hierarchical architecture. Most common techniques such as extrusion, freeze structuring and shear cell technology fall into this category (Dekkers et al., 2018).

3.1. Extrusion

Extrusion is a thermomechanical process that is commonly employed for the extraction of proteins from soy (Preece et al., 2017). Extrusion results in texturization of the soy; based on the moisture content maintained during this process, this technique can be categorized as low moisture and high moisture extrusion (Lin et al., 2002). Low moisture extrusion (<35 %) of soy yields a protein-rich product that is soft, sponge-like, has high water holding capacity which is applicable for the preparation of sausages and patties. Meanwhile, high moisture extrusion results in improved gelling and emulsifying properties which are desirable qualities to develop products that simulate meat like features similar to poultry and fish (Wittek et al., 2021).

Thermal extrusion process employs a power heater which is traditionally used to texturize meat products. In this process the plant-based materials are pretreated with water and oil to create an emulsion which is then pumped through the power heater where it gets heated which results in the coagulation of proteins. This results in a texturized material that is laminated and fibrous in nature (Sun et al., 2022).

3.2. *Fibre spinning*

Fibre spinning involves development of protein fibres by passing it through a dye that consists of holes with diameters ranging from of 50 to 250 μm. The plant-based proteins are initially solubilised in alkali and passed through the dye which is captured in a bath containing acid and salt. This coagulates the protein to obtain insoluble fibres which are washed, neutralised, spin-dried and immersed in binding agents (Bakhsh et al., 2021).

3.3. *Shear cell technology*

Shear cell technology is an innovative method to develop meat like plant-based products. Although this technology is ideal to create plant-based steaks, shear cell technology is still in pilot stage. In this device, a Couette Cell which works on the principle of a rheometer is used to structure proteins in steak-like products. A blend of plant-based materials is subjected to shear force via a rotating plate and a stationary cone. Temperatures between the range of 90–110 °C maybe applied to the plant material to obtain the desired characteristics. The plate rotates at a speed of 5–25 rpm and processing time varies between 5 and 25 min. This device is exceptional in creating steak-like material from plant-based proteins that is layered, fibrous, textured, and mouthfeel that resembles real meat (He et al., 2020).

3.4. *Mixing with hydrocolloids*

In this method, protein sources are mixed with hydrocolloids that precipitate with multivalent cations. The resulting fibrous product is pressed to remove excess water. The final product obtained by the application of this technique does not possess the shear direction compared to other methods and thus can only be used to produce minced meat equivalents such as schnitzel burgers. A common example of a hydrocolloid that is employed in this method included alginates (Kweldam et al., 2011).

3.5. *Freeze structuring*

Freeze structuring is a process by which a slurry of proteins is frozen unidirectionally to obtain anisotropic structures. The aqueous solution is frozen where the rate of freezing is controlled to obtain ice crystals of predetermined sizes. The frozen slurry is then subjected to drying so that the final product has a parallel sheet-like formation. It is imperative that the proteins subjected to this method should be completely soluble in the slurry prior to freezing (Lugay & Kim, 1978).

4. Digestibility and physicochemical properties of alternative proteins

A healthy adult is suggested to consume at least 0.8 g of protein per kg body weight per day, and this requirement increases to 1–1.2 g of protein per kg body weight after the age of 65, to maintain the quality of life. Muscle synthesis and regeneration in itself requires an intake of about 25–30 g high quality proteins containing at least 2.5–2.8 g leucine per meal (Bauer et al., 2013; Bhat et al., 2021; van den Helder et al., 2021). There has been a continuous increase in global demand and consumption of protein through conventional sources such as meats, beans and dairy products, and among these, muscle proteins are the most common sources that have been consumed across many cultures.

Protein digestibility or the true ileal digestibility is defined by the FAO as the difference (after correction of the endogenous and basal amino acid losses) between the amount of amino acids that are ingested and those that are recovered from ileum digesta (Lee et al., 2016). Protein digestibility is a crucial factor that describes its susceptibility to proteolysis and determines the nutritional and metabolic outcome in the body. Faster digestion of the protein positively correlates to its postprandial gain especially with ageing (Dangin et al., 2003). The undigested proteins and dietary as well as endogenous proteinaceous substrates enter the large intestine for further proteolysis or fermentation by the gut microbiome. However, this leads to release of nitrogenous by-products such as amines and ammonia, indolic, phenolic, N–nitroso and cresolic compounds that are harmful to the gut homeostasis and have been known to cause inflammatory bowel disease and colorectal cancer among others (Peled & Livney, 2021). While detoxification reactions of such metabolites exist, it is much more effective to reduce the generation of such by-products by effective protein absorption. The dietary protein absorption and by-product generation largely depends on the structure, molecular weight, solubility, source and processing history of the food, and accessibility to the digestive enzymes (Dallas et al., 2017).

Previous studies have shown that the digestibility of dietary proteins obtained from plants (Table 3) is lower than those obtained from animal sources. However, this could be potentially improved with the advent of novel food processing technologies (Kaur et al., 2016; Sá et al., 2020). Different methods of protein modification/processing and their influence on protein digestibility are summarised in Fig. 2. Some of these processing techniques are listed below.

Table 3
In vitro protein digestibility values for different alternative protein sources reported in the literature. (Adopted from Kaur et al., 2021 with permission).

Source	Protein type	Processing method	In vitro protein digestibility (IVPD, %)	Reference(s)
Pulse	Cowpea	Cooked	87–98	Khattab et al. (2009)
	Pea	Cooked	73–94	Khattab et al. (2009)
	Pea protein isolate	Uncooked	87.2	Schimbator et al. (2020)
	Kidney bean	Cooked	64–87	Khattab et al. (2009)
	Chickpea	Raw and soaked	74.3	Han et al. (2007)
	Lentil flour	Uncooked	75.90–77.05	Barbana and Boye (2013)
	Lentil protein concentrates	Uncooked	82.80–83.20	Barbana and Boye (2013)
	Hemp	Uncooked	78.5	Schimbator et al. (2020)
	Soybean	Raw and soaked	71.8	Han et al. (2007)
	Soy protein isolates	Uncooked	85.9	Schimbator et al. (2020)
Cereal	Wheat	Cooked	85.5	Mertz et al. (1984)
	Maize	Cooked	85.3	Mertz et al. (1984)
	Rice	Cooked	83.8	Mertz et al. (1984)
	Sorghum	Cooked	56.8–63.2	Mertz et al. (1984)
	Sorghum	Extruded	79	Mertz et al. (1984)
	Millet	Cooked	74.8–85.5	Mertz et al. (1984)
	Oat protein concentrate	Uncooked	77.5	Schimbator et al. (2020)
Others	Protein from Pleurotus mushrooms	Uncooked	68.2	Schimbator et al. (2020)
	Sea buckthorn protein	Uncooked	76.2	Schimbator et al. (2020)
	Algal protein	Extracted	78.4–88.9	Tibbetts et al. (2016)

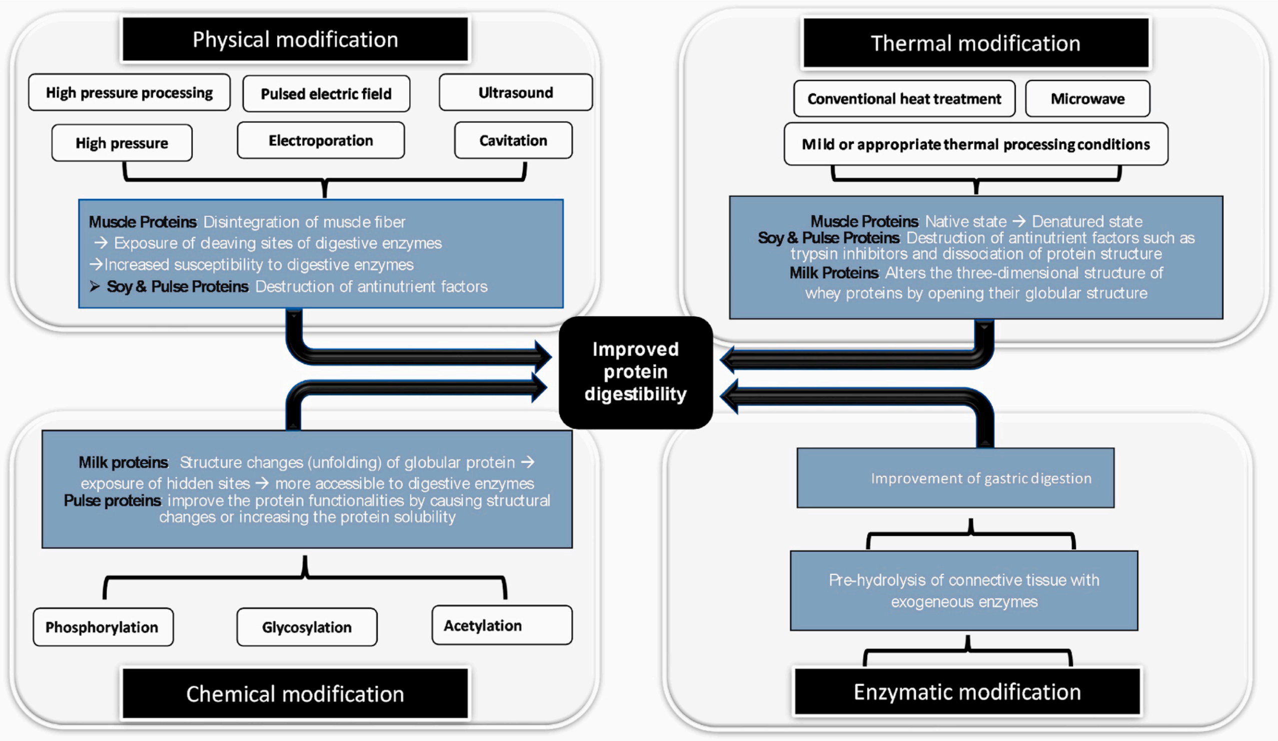

Fig. 2. Different methods of protein modification/processing and their influence on protein digestibility (Adopted from Kaur et al., 2021 with permission).

4.1. *Thermal and thermomechanical processing*

Heating modifies the protein structure which in-turn either increase or decrease the accessibility of cleavage sites by mechanisms such as formation of hydrophobic aggregates (Gulati et al., 2017). The proteins can also differentially expose their aromatic residues upon heat treatment, and thus provide more targets and affinity for pepsin to act on (Zhao et al., 2022). Temperature treatment allows protein systems to undergo aggregation and controlled denaturation which causes functional changes such as gelation or emulsification (Akharume et al., 2021). However, the denaturation and aggregation patterns of proteins are not predictable for a given heat treatment process and could thus produce a wide range of non-reproducible protein functionalities (Bhat et al., 2021). The thermal processes used are ultra-high-temperature, convectional cooking, boiling, sterilisation, flash pasteurisation, frying, baking, autoclaving or poaching. Studies have also demonstrated that such heating processes not only increases protein digestibility but also reduces anti-nutritional and inferior functionalities of plant proteins arising from their compact structures or higher molecular weights (Nikbakht Nasrabadi et al., 2021).

When heat (95–160 °C) is combined with mechanical processing such as extrusion or shear cell technologies, not only does this reduce the anti-nutritional properties of plant proteins, but also result in a meat-like fibrous structure of plant proteins, thereby enhancing both its functional and sensorial properties (Beniwal et al., 2021; Palanisamy et al., 2019). The transformation is either caused by energy-induced Cys ß-elimination that forms covalent bonds leading to Maillard reaction, increased dehydroalanine, and lanthionine, or restructuring by residue aggregation that forms heavily cross-linked aggregates and a complete loss of tertiary structure and helices upon cooling (Beniwal et al., 2021).

4.2. *Ultrasound*

Like thermal treatment, high intensity ultrasound also causes partial unfolding, aggregation and cross-linking of proteins in order to expose the cleavage sites, hydrophobic stretches and sulphuryl sites and reduce trypsin inhibition in soymilk (Vanga et al., 2020). Ultrasound treatment can also contribute to cleaving the peptides by disrupting non-covalent bonds and interactions. A 20 kHz ultrasound treatment of amplitude 60 % for 10 min in pulses of 10 s followed by 5 s off-time was found to improve the protein digestibility as well as surface activity of buckwheat protein by up to 17 % as compared to the untreated protein (Jin et al., 2021). Some of the other effects of high intensity ultrasound on plant proteins include enhanced viscoelastic and antioxidant properties, free radicle induced fragmentation, reduced allergenicity, altered secondary and microstructures, and formation of relatively smaller fragments upon enzymatic digestion when compared with untreated proteins. This might be due to the acoustic cavitation induced free radicle formation in the ultrasound treated proteins (Bagarinao et al., 2020; Jin et al., 2021).

4.3. *Microwave*

High frequency microwave can unfold the protein and increase its digestibility as well as digestion kinetics by acting on the dipole moment of water molecules in the food. The heat generated can disrupt the non-covalent interactions such as hydrogen and disulphide linkages (Bhat et al., 2021). In soymilk, microwave treatment at 85 °C for 10 min has been reported to significantly reduce processing time, energy requirements, anti-nutrient properties and trypsin inhibitors, while increased the digestibility and bioavailability (Vanga et al., 2020). However, extended microwave treatment has also shown a reduction in protein digestibility and its nutrient availability due to reduced loops, increased ß sheets, reduced relative concentration of Lys and thus formation of crosslinks by Maillard reaction or oxidation of sugars in proteins from sources such as rice bran and gluten (Phongthai et al., 2016; Xiang et al., 2020; Luo et al., 2018).

4.4. *Pulsed electric field*

When short pulses of voltage as high as 1–80 kV/cm is applied liquid or semi-solid food placed between the electrodes, it's known to affect the protein confirmation and unfolding mechanisms while causing negligible damage to the food quality (Munekata et al., 2020). Depending on the nature of protein and voltage applied, this could improve the protein digestibility and reduce its immunological response (Bhat et al., 2021). While low intensity electric field is reported to improve the organoleptic properties of the protein by inducing electroporation, membrane permeabilization and protease diffusion, higher intensities can ionise or disrupt the electrostatic interactions which in turn disrupts the secondary and tertiary structure of the protein (Chian et al., 2019). Extended effects of pulsed electric field treatment includes faster and greater digestion kinetics regardless of the protein type (Bhat et al., 2021). When combined with cooking, pulsed electric field treatment was reported to enhance the protein digestibility by releasing free amino nitrogen (Chian et al., 2019).

4.5. High pressure

A high temperature treatment of the proteins under a pressure between 100 MPa and 300 MPa for a fixed time can change the protein conformation or expose the clevage sites due to partial aggregation, denaturation or geletion (Kaur et al., 2016; Xue et al., 2020). Higher pressures such as 600 MPa in proteins caused surface texture changes and crumbling which not only cooked it but also allowed greater surface accessibility of pepsin upon gastric digestion (Ye et al., 2017). Even higher pressure treatment is classified as ultra-high-pressure homogenisation process, and such a treatment under mild temperature is known to reduce the allergenicity of plant-based beverages due to retention of lysine content and conformational changes to reduce gut immune response (Hu et al., 2017; Munekata et al., 2020). In proteins from the pulses such as lentil and fava, high pressure pre-treatment cased a reduction in trypsin inhibition (Hall & Moraru, 2021).

4.6. Enzymatic treatment

A balanced application of proteolytic and non-proteolytic enzymes on alternative proteins are known to alter their structure and consequently increase their digestibility. Similar strategies have already with animal proteins of low digestibility such as stromal proteins and reducing the muscle structure in beef brisket (Zhu et al., 2018). Treatment of Hemp seed proteins with carbohydrases and phytases followed by ultrafiltration was noted to increase absorption relative to untreated and commercial concentrates (Malomo & Aluko, 2015). In addition to enhancing digestability, enzymatic pre-hydrolysis can reduce the immune reactivity by collapse of conformational epitopes and digestion of linear epitopes which ultimately reduces the effect of allergens in gastrointestinal digestion of the protein. For complex mixtures of proteins of variable digestibility, enzymatic treatment post-hydrolysis can increase the purity as seen in amylase based microfluidisation of rice proteins which filtered indigestible proteins such as prolamin and globulin and retained digestible proteins such as glutelin (Xia et al., 2012). In case of protein extraction and processing from legumes such as chickpea and pea, aqueous extraction mediated by hydrolytic enzymes such as papain, pepsin, alcalase and trypsin, enrichment of free amino acids and pure fractions of digestible proteins increased the digestibility (Xia et al., 2012).

4.7. Glycosylation, phosphorylation and acetylation

Glycosylation of proteins could be carried out nonenzymatically by heating and molecular crowding as an initial step in the Maillard reaction. This leads to unfolding of indigestible globular proteins, thus exposing the surface for digestive enzyme upon consumption leading to higher digestibility. Dextran induced glycosylation of rice protein has been reported to increase the digestibility (Cheng et al., 2021). In Whey protein however, glycosylation may either increase or decrease digestibility since glycosylation in this case causes not only unfolding but also a steric hindrance and thus the two changes must be balanced to optimise digestibility (van Lieshout et al., 2020). Another instance where glycosylation can reduce digestibility is by blocking Lys residues and cross-linking which in turn reduces the accessibility the target cleavage sites for proteases (van Lieshout et al., 2020). Whey protein contains beta-lactoglobulin which is an allergen, however it's covalent bonding with reducing sugars during glycosylation disrupts it's interaction with Immunoglobulin E and thus reduce the allergenicity and indirectly enhance digestibility. In fact, it has been reported that physical-assisted chemical methods such as ultrasound, pulsed electric fields, high pressure and microfluidization as a pre-treatment prior to glycosylation allows higher extent of glycosylation of beta-lactoglobulin thus enhances the anti-allergenic outcome when compared with the chemical glycosylation alone (Shao et al., 2020).

Gliadins are partially resistant to gastric enzyme-based digestion; however, a prior phosphorylation reduces this effect and thus enhance the digestibility (Xue et al., 2019). Allergens such as Fag e 2 which is generally resistant to pepsin can also be digested better when phosphorylated by heating as a pre-process (Ahmad et al., 2020).Finally, the protein solubility is observed to increase, accompanied by structural modifications that enhance functionality when acetylated by treatment with acetic anhydride or succinic anhydride of suitable concentration. An increased in-vitro digestibility due to acetylation has been reported in Kidney beans (Yin et al., 2009).

5. Nutritional equivalency, bioavailability and food safety concerns

The need for environmental sustainability is inevitably and significantly related to nutritional sustainability and this interdependence has been increasing with raise in human population and dietary demands which has consequently led to higher environmental burden barricading the 1.5 °C target climate change (Clark et al., 2020). This also complements the increasing malnutrition and micronutrient deficiency in the global population (Green et al., 2021). Thus, alternative proteins and future food-based context-specific diet shift is crucial for sustainable improvements to the environment and health. It is however essential to not only to optimise the alternative protein processing for better nutritional value and reduced environmental impact, but also understand and define the optimal protein sources and diet plans.

5.1. Nutritional sustainability

The most obvious nutritional sustainability that can be realised with alternative protein-based diet shift is the reduced risk of acquiring lifestyle and dietary diseases such as coronary heart disease and colorectal cancer that is often correlated with meat consumption. However, it is important to evaluate thus benefit with the reduced nutrient bioavailability and equivalency in purely plant-based diet. While plant sources improve the concentrations of poly-unsaturated fats, folate, sugars, salts and fibres and reduce saturated fat intake; it is known to cause deficiencies of proteins, iron, vitamin B-12 and zinc (Vatanparast et al., 2020; Farsi et al., 2022; Harnack et al., 2021). While studies have concluded that plant-based food have reduced refined carbohydrates, cholesterol, saturated and *trans*-fat relative to animal sources (Frontier and Liechtenstein, 2020) —, this has also been contradicted for some plants sources that were found to have similar saturated fat content as meat (Bohrer, 2019). When specifically comparing the protein composition in plant sources against the conventional sources, Lysine, Methionine, Threonine and Tryptophan were found to deviate in their relative abundances (Ru et al., 2020; Tang et al., 2019). Anti-nutritional factors that are known to block mineral absorption, such as phytates, oxalates, and lectins that are common in grains, leafy vegetables and legumes, lack sufficient understanding and thus considerations at the time of future food processing (Parodi et al., 2018). Another qualitative factor for consideration includes the protein quality comprising of folding, secondary and tertiary structure, amino acid composition all of which impact the digestibility and reactivity (Ru et al., 2020).

Nutritional equivalency studies attempt to overcome this difference in the absorption and metabolism of nutrients from conventional and alternative food sources. However, the equivalency is not only the nutritional content in these food sources being similar, but also that their bioavailability, bioaccessibility and bioactivity being comparable. For instance, van Vliet et al., 2021 reported that even though the nutrient profile of grass fed beef and plant-based food was equivalent, the metabolic profile was different by up to 90 % (van Vliet et al., 2021). Such nutritional equivalency studies seem to generally conclude the common idea of there being significant limitations in nutrient modelling studies and that a dietary model incorporating plant, insects, fungi, microbes and algae based alternative protein sources overcomes the vitamin B-12, A, iron, protein and fatty acids deficiency (Tang et al., 2019; Caporgno & Mathys, 2018; Parodi et al., 2018). Infact Green et al., 2022 concludes in its extensive review, that the most nutritionally sustainable diet would objectively be a flexitarian diet consisting of majorly plant-based alternative protein and future food consumption with a relatively reduced and context dependent meat consumption (Green et al., 2022).

Apart from the direct nutritional and health impacts, alternative proteins also have an indirect impact through the food security dimension. With animal-based proteins, there has been a well-studied toxicity due to bio-magnification of heavy metals and other chemical and microbial contaminants as well as pathogens, however, plants are also known to accumulate similar toxins along with pesticides, mycotoxins and microalgae (Van der Spiegel et al., 2013). A more prominent concern with plant-based food is the larger spectrum of allergens (Jones, 2020). These concerns call for the attention of appropriate processing protocols that eliminate these concerns while also not affecting the matrix and quality of the food negatively (Kraak, 2022; WHO report, 2021).

Such drastic diet shifts also requires an introspection on ultra-processing and technology availability, allergenicity and food safety considerations of alternative proteins. Development of sustainable and novel processing and post-processing techniques and pipelines is not only essential for the marketability of such future food, but would also significantly improve the bioavailability, bioactivity and bioaccessibility of proteins and other nutrients in terms of it's absorption and utilization while blocking the activity of anti-nutrients (Canelli et al., 2020). On the other hand, a non-critical approach such as bridging the nutrient deficiencies with supplements will not only prevent the scientific development of the future food but also raise further concerns on environmental sustainability.

5.2. Environmental sustainability

The demand of natural resources for the synthesis and processing of conventional and alternative proteins are specific and distinct. While the animal-based food demands a large land availability, the plant-based food production has a significantly higher energy demand. The release of greenhouse gases at the time of cultivation as well as processing of both these proteins are comparable over a longer time period. However, the processing technology and pipelines for plant-based alternative proteins is mostly novel and unoptimised and thus promises a large scope of improvement in the near future. The novel nature of these processing techniques also calls of scepticisms regarding their scalability from pilot scales to economic scales and more importantly the environmental impact of the economic scale. Since these techniques are still at an innovative phase, any predictions about their environmental impacts soon after appropriate scaling and optimisation is hard to make. The impacts of climate change when combined with the impacts on human health due to the environment is considered, plant-based food show the most ideal alternative when compared to cultured meat and proteins from conventional animal sources (Smetana et al., 2015) and such results can only be expected to improve with better energy decoupling and decarbonization technology.

Microalgae as an alternative source of protein could be of the photoautotrophic, heterotrophic or mixotrophic variety and have accordingly been successfully processed at pilot scales using fermenters or even outdoor ponds requiring less land resource but more energy. Organic substrates have shown a higher algal concentration, but other choices also include residues or food wastes (Smetana et al., 2017). Microalgae can be grown sustainably in a variety of environments, including seawater, brackish water, and wastewater, and they require fewer resources, such as water and land, compared to traditional protein sources like beef or soy. Algae can reduce the environmental impact of protein production compared to traditional protein sources, as they produce fewer greenhouse gases and have a lower land and water footprint (Magpusao et al., 2021). Moreover, microalgae can fix carbon dioxide from the atmosphere and use it as a source of energy and carbon, reducing the net greenhouse gas emissions associated with protein production compared to traditional sources. Microalgae have several advantages as a protein source, especially in terms of sustainability. They grow quickly and can produce a high yield of biomass per unit of land and water, making them an efficient and environmentally friendly option for protein production. Additionally, they do not require arable land or freshwater resources, which are often in short supply. However, it is important to note that the commercial production of microalgae as a protein source is still in its early stages, and further research and development is needed to optimize the processes and make it economically feasible on a large scale. Another example would be mycoprotein as an alternative source which also shares a similar low land use along with lower emission of greenhouse gases (Parodi et al., 2018). However, Smetana et al., 2015 have concluded that mycoproteins would have similar environmental impacts as chicken and that these are hard to confirm due to limited studies being available for mycoproteins (Smetana et al., 2015).

Another consideration of environmental sustainability for alternative proteins would be the processing energy. While the animal sources have been processed conventionally using non-renewable fuels such as fossil fuels, the alternative protein processing technology uses renewable and novel energy sources. However, such technology also demands for rare earth materials and land resource while also being financially heavy and more skill intensive. The novel technologies also lack suitable environmental assessments to determine it's reliability and sustainability. Low technology readiness further contributes to higher input variation, lack or reproducibility, unoptimised operation, lower economic benefits and yields. However, to counteract this, plant-based alternative proteins generally have lower environmental footprints with a broad opportunity and prospect to improve even further (Heller & Keoleian, 2018; Smetana et al., 2015). The meat industry, cultured meat and insect processing plants all use a variety of antibiotics for both breeding and controlling the contamination. They thus share a major concern of antibiotic overuse which has led to antibiotic resistance and related deaths (Murray et al., 2022; Van der Spiegel et al., 2013). Such a concern doesn't exist for plant, algal and fungal protein sources.

6. Alternative proteins and food laws

Food laws and regulations play an important role in the development and sale of alternative protein products. It is important for companies producing and selling alternative proteins to be aware of these laws and regulations, as they can have a significant impact on the success of their products in the market. The labelling and marketing of alternative protein products is regulated by government agencies like the European Food Safety Authority (EFSA), the US Food and Drug Administration (FDA) and the US Department of Agriculture (USDA). These agencies ensure that the labelling of alternative protein products is truthful and not misleading, and that the products meet food safety standards.

In the European Union (EU), there are several laws and regulations related to plant-based protein products, that covers food safety and labelling requirements. European Union's regulation on novel foods, which outlines the procedures and requirements for the approval and labelling of new and innovative food products, including alternative proteins (Lähteenmäki-Uutela et al., 2021). The General Food Law Regulation (EU) No. 178/2002 sets out the principles for food safety in the EU, including the requirements for traceability, labelling, and food safety assessment (European Regulation, 2002). The Food Information to Consumers Regulation (EU) No. 1169/2011 requires that the labelling of food products accurately reflects the ingredients and nutritional value of the product, including the presence of plant-based protein (European Union, 2011). The Novel Foods Regulation (EU) No. 2015/2283 establishes a framework for the authorization of novel foods, which includes plant-based protein products that have not been traditionally consumed in the EU (European Union, 2015; de Boer & Bast, 2018). Overall, these regulations aim to ensure the safety and accuracy of labelling of plant-based protein products in the EU, and to provide consumers with the information they need to make informed choices about the food they purchase and consume.

Similarly, the Food and Drug Administration (FDA) is responsible for regulating food products in the USA, including those that are made from plant-based proteins. The FDA sets standards for labelling and nutrition information for food products, as well as for food safety (FDA, 2013). The FDA has established that plant-based proteins, such as soy and pea protein, can be used as a source of protein in food products, provided that they meet the standards set by the agency (FDA, 2006). The FDA also requires that plant-based protein products be labelled accurately and truthfully, with information about the ingredients and nutritional content (FDA, 2022). In recent years, there has been a growing trend towards plant-based diets, and an increasing number of food products made from plant-based proteins have entered the US market (Mintel Report, 2022). The FDA is actively monitoring this trend and is working to ensure that these products are safe and properly labelled. Overall, the FDA recognizes the importance of plant-based proteins as a source of nutrition, and is committed to ensure that these products are safe, properly labelled, and meet the agency's standards for quality and nutrition.

The Singapore Food Agency (SFA) has also established guidelines for the safety assessment of new and innovative food products, including alternative protein products. These guidelines aim to ensure that these products are safe for consumption and meet the standards set by the SFA for food safety and quality. The guidance outlines the information that companies need to provide in order to obtain approval for their products, which include data on their ingredients, production methods, and any potential health risks associated with consuming the products (SFA, 2021). Similarly, the Japanese government recognizes the potential of alternative proteins. While the existing regulatory regime in Japan may cover alternative protein products, depending on the production method, the government is taking steps to develop a specific regulatory framework for these products to ensure their safety and increase consumer confidence (Sasatani, 2020). Food Standards Australia New Zealand (FSANZ) is a joint food regulatory agency responsible for developing and enforcing food standards in both Australia and New Zealand. Currently, FSANZ has not yet developed specific regulations for alternative protein products, but it intends to evaluate these products under its existing novel foods framework. This means that FSANZ will consider applications from companies that produce alternative protein products and use that information to determine what specific regulations are needed to govern the production, sale, and consumption of these products (Food Standards, 2022).

7. Commercial potential, consumer acceptance and future prospects

7.1. Commercial potential

The alternative protein market has been growing rapidly in recent years due to increasing consumer demand for healthier and environmentally sustainable food options and increasing inclination towards veganism. The trend towards plant-based diets and the growing health concerns surrounding animal-based protein have contributed to the growth of the alternative protein market. Additionally, advancements in food technology have made it possible to produce plant-based protein that has similar taste and texture to animal-based protein, making it a more appealing option for consumers. Companies are also investing in research and development to create new plant-based protein products, which is further driving the growth of the market. This has motivated several industries to skew or even establish on the basis plant-based proteins, some of the influential ones currently being 'Beyond Meat' and 'Impossible Foods'. Media companies such as 'The Good Food Institute' have significantly contributed to the uprise of alternative proteins industries and their manipulation of consumer acceptance. However, these industries rely on technology and production pipelines that are still in their initial stages of development, and thus the accessibility of alternative protein sources is significantly lower. The lower accessibility and higher costs of production and retail are major hurdles in increasing consumer acceptance (Plant-based and cultivated meat innovation: GFI, 2023). It is important to note that the alternative protein market is still in its early stages and faces challenges such as scaling up production, reducing costs, and improving the taste and texture of the products. However, with the increasing demand for alternative proteins and advancements in associated technologies, the market is expected to continue to grow tremendously in the coming years.

The global alternative protein market has reached US$ 14.76 billion in 2021 and is projected to grow US$ 36.61 billion by 2030, recording a compound annual growth rate of 12.4 % during the forecast period (Meticulous Research, 2022). According to a report by Markets and Markets (2022), the global plant-based protein market was valued at US $16.3 billion in 2019 and is projected to reach US$33.2 billion by 2026, growing at a compound annual growth rate (CAGR) of 11.4 %. Considering the market trends, it appears that alternative protein have good market potential to grow as an alternative to animal-based protein products.

7.2. Consumer acceptance and future prospects

The commercial potential of alternative proteins is strongly staggered by the consumer acceptance of the product. It is therefore critical to not only model the reason for the consumer acceptance response but also influence it positively. A key strategy to achieve this could be knowledge and education. Alternative proteins are subject to scepticism primarily due to their novel nature and relatively newer production technology. However, the knowledge of the production technology along with novel and innovative substrates could itself drive the consumer to higher acceptance levels. Consumer needs to be educated and made aware of these alternative options via both critical review of current research developments and a persuasive medium of communication. Persuasion could be in the form of better presentation of information as well as the use of more impactful forms of communication (such influencer marketing, targeted advertising and social media campaign) (García-Segovia et al., 2020). Interestingly, the market for plant-based proteins is benefited and sustained more dominantly due to the flexitarian and non-vegetarian consumer class when compared with the vegan and vegetarian consumers. This paradoxical effect could be due to the higher number of consumers belonging to the former than the latter (Green et al., 2022). It thus becomes more essential for the alternative protein marketing to be steered towards the non-vegetarian and flexitarian consumer acceptability rather than the current models that target the vegetarian and vegan consumers who are already incentivised towards alternative proteins by their choice limitation (Plant-based and cultivated meat innovation: GFI, 2023). This can be achieved by emphasis towards the aspects of alternative proteins that clearly advantageous against conventional protein sources, such as it's health, economic and environmental sustainability.

The European food-related-lifestyle (FRL) framework correlates consumer's food choices with a corresponding food-related behaviour and by extension, decision making and personality types such as adventurous, conservative, rational, careless or uninvolved classifies the consumer that try novel food types as adventurous. This indicates that the marketing could be targeted to such consumers while positively educating the other consumers who are restricted by food neophobia, disgust sensitivity or other mental constructions. The latter can be achieved by emphasis to environmental and health benefits of alternative proteins reviewed in this paper.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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