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REVIEW

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Trends and innovations in the formulation of plant-based foods

Christabel Tachie[1], Ifeanyi D. Nwachukwu[2] and Alberta N. A. Aryee[1*]

Abstract

Globally, the production, distribution, sale and consumption of plant-based foods (PBFs) are on the increase due to heightened consumer awareness, a growing demand for clean label products, widespread efforts to promote and embrace sustainable practices, and ethical concerns over animal-derived counterparts. This has led to the exploration of several strategies by researchers and the food industry to develop alternative milk, cheese, meat, and egg products from various plant-based sources using technologies such as precision fermentation (PF), scaffolding, extrusion, and muscle fibre simulation. This work explores current alternative protein sources and PBFs, production trends, innovations in formulation, nutritional quality, as well as challenges restricting full utilization and other limitations. However, PBFs have several limitations which constrain their acceptance, including the beany flavour of legumes, concerns about genetically modified foods, cost, nutritional inadequacies associated micronutrient deficiencies, absence of safety regulations, and the addition of ingredients that are contrary to their intended health-promoting purpose. The review concludes that investing in the development of PBFs now, has the potential to facilitate a rapid shift to large scale consumption of sustainable and healthy diets in the near future.

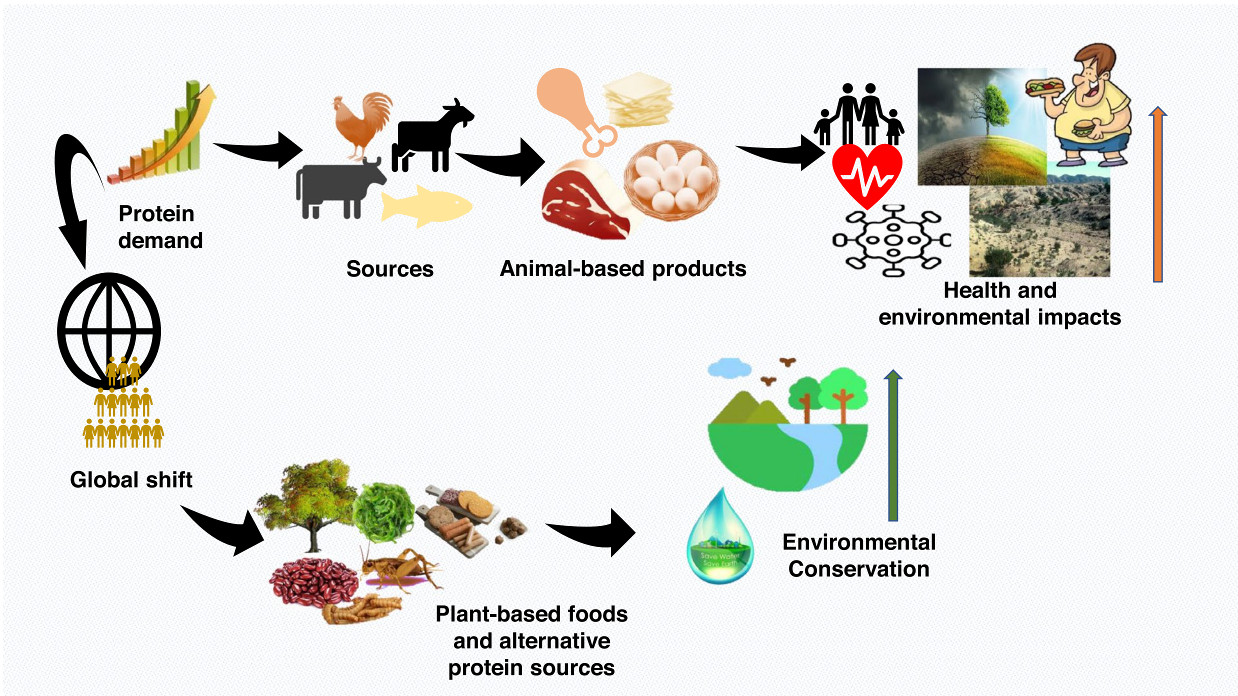
Highlights

- Various novel food products have been developed from plants
- Animal-derived foods have a higher risk of diet-related metabolic disorders
- Improving PBF characteristics and nutrient composition will increase patronage
- PBFs production is more environmentally friendly than animal-derived foods
- PBF industry still in its infancy requiring adequate safety regulations and quality standards

Keywords Plant-based foods, Vegetarian diet, Sustainability, Healthy diets, Precision fermentation

*Correspondence:
Alberta N. A. Aryee
aaryee@desu.edu
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Consumers' concern about their choice of food, and their possible health and environmental implications has led to noticeable changes in dietary patterns and a growing shift to the consumption of PBFs, mostly for the purpose of promoting healthful living, conserving animal life and enhancing environmental sustainability (Bresciani & Marti 2019; Estell et al. 2021; Małecki et al. 2021; Nychas et al. 2021). There now exists an increased consciousness among many consumers to adopt PBFs due to ethical concerns, campaigns to reduce livestock use and meat consumption by animal rights/welfare organizations, and the heightened emission of environmentally harmful greenhouse gases (GHG) as a result of animal-based food production (M. Kumar et al. 2022). Other drivers include excessive use of resources, urbanization, improper distribution of protein intake (overconsumption) in developed countries often with negative health implications, as well as population growth (Aschemann-Witzel et al. 2020; World Economic Forum 2019).

Several studies have shown that PBFs help to delay the onset, reduce the risk of and even prevent certain disease conditions (Bowman 2020; Kahleova et al. 2017; Kim et al. 2019). Aside from macro-nutrients such as proteins, PBFs also contain wide variety of carbohydrate types with varying role in the development of a diverse intestinal flora and a substantial amount of micronutrients such as vitamins, minerals, and bioactive compounds (Hever & Cronise 2017; Samtiya et al. 2021). For instance, soy products also represent a good source of calcium and isoflavones which may help maintain healthy bones and lower the incidence of osteoporosis (Qin et al. 2022).

However, PBFs are generally lacking in certain essential amino acids and are consequently regarded as incomplete proteins (M. Kumar et al. 2022). It has been reported that the consumption of PBFs reduced the risk of cardiovascular disease, enhanced cardiovascular health, controlled glycaemic levels, as well as lowered blood cholesterol level, obesity, and blood pressure (Kahleova et al. 2017; Kim et al. 2019). PBFs in the form of soy products partially substituted for meat have been shown to improve insulin sensitivity (Van Nielen et al. 2014) and enhance the gastrointestinal response to regulate glycaemic index (Kahleova et al. 2017). In addition, plant-based products such as meatless burgers from Beyond Meat® and Impossible Foods® contain no cholesterol and are designed to have significantly lower saturated fat contents than traditional beef burgers (Zheng et al. 2019).

The Agri-food system is simultaneously a significant contributor to and at risk of adverse climate change events due to the emission of GHGs in the normal course of agricultural activities such as livestock production. Lifestyle changes and specifically changes in eating habits have been reported to promote environmental sustainability (Semba et al. 2021). For instance, eating according to the Eatwell plate will minimize GHG emissions and land use by 45% and 49%, respectively (Askew 2022b). Replacing meat-based diets with PBFs has the potential to enhance soil enrichment through nitrogen fixation, as well as decrease water use and reduce the carbon footprint (Keshavarz et al. 2020; Semba et al. 2021).

Conventional protein

Conventional sources of proteins such as red meat, poultry, dairy products, eggs and seafood typically represent the source of the majority of proteins used as food, with protein content ranging from the lowest in eggs (51%) to the highest in the milk protein, calcium caseinate (86–93%) (Atallah et al. 2021; Gorissen et al. 2018). Animal-based protein sources are regarded as high-quality since they contain essential amino acids that are needed for the various metabolic functions in the body. Bovine milk contributes up to 85% of milk consumed globally with a protein content of about 3.4% and contains all the essential amino acids in large amounts (Małecki et al. 2021). In red meat, total protein content ranges from ~ 19—31% (Boler & Woerner 2017). The average protein content of whole and freshly-laid egg is approximately 12.6% with the egg white contributing about 10% of the total proteins (Boler & Woerner 2017; Réhault-Godbert et al. 2019; Salter 2019). In addition to their considerable protein content, eggs also have the added advantage of being low in calories and more affordable compared to red meat (Małecki et al. 2021). Although animal-based proteins are very nutritious, highly digestible and bioavailable (Aschemann-Witzel et al. 2020), frequent consumption of red and processed meats (including bacon, ham and sausage) has been linked to diseases such as cancer, type-2 diabetes and obesity (Salter 2019; Zheng et al. 2019). Given the world's burgeoning population, longer average lifespan and higher average purchasing power, the corresponding increase food demands and nutritional requirements underlines the urgent need for exploring novel sources of food proteins (Salter 2019).

Plant-based sources

Plant-based protein sources include legumes, seeds and nuts, and by-products/waste from food production have been studied and utilized to simulate meat and other analogues. Their nutritional and functional properties, health benefits and food applications are described below.

Legumes

Pulse is coined from the Latin word "puls" and belongs to the legume family grown for its edible seeds (Semba et al. 2021; Tidåker et al. 2021). All pulses are legumes but not vice versa. Legumes are distinct from pulses as "pods or fruits" containing seeds or dry grains (S. Kumar & Pandey 2020). Legumes are affordable, nutrient-dense, and excellent sources of protein, dietary fibre and minor nutrients such as iron and vitamins, and include lentils, chickpeas, pinto beans, red kidney beans, soybean, peanuts, and fresh pod beans (Keshavarz et al. 2020). Recently, an Israeli company developed a new protein isolate from their cross-bred pea with about 65—72% protein to be used as a base in plant-based products with improved nutritional benefits and functional properties including high solubility, emulsification and gelation (Southey 2022a). Due to the lower glycaemic index of legumes and their high dietary fiber content, regular consumption can help maintain normoglycemia and lower the risk of cardiovascular diseases (Bresciani & Marti 2019; Mullins & Arjmandi 2021). Legumes are a generally healthier replacement for conventional meat and for improved nutritional value, they can be complemented with other plant sources such as cereals (Proveg 2019). It has also been reported that incorporating pulses into meat products reduces lipid oxidation, microbial spoilage and also enhances the functional properties in the samples such as swelling, emulsification and water/oil holding capacity (Mulla et al. 2022; Purohit et al. 2016). For instance, adding red lentils, green peas and grass pea flour to pasta improved its nutritional characteristics and served as a natural colour additive (Teterycz et al. 2020). The color effect was contributed by carotenoids and chlorophyll in the seed coat and cotyledons of bean samples with the red lentil showing the highest colour intensity (Teterycz et al. 2020).

Seeds and nuts

Seeds and nuts such as flaxseed, peanuts and almonds are notably high in proteins, but are generally lacking in certain amino acids, making them insufficient in meeting amino acid needs e.g., peanuts lack valine and lysine. Others including cottonseed, sunflower seed, sesame seed, pumpkin seed, hazelnut, grape seed, walnut, canola seed, hemp seed and canola are important oilseed crops with relatively high protein meal content (Accesswire 2022a; Langyan et al. 2022). Some seeds such as pumpkin, sunflower and hemp have also been used to produce alternative eggs, cheese and flour products respectively (Accesswire 2022b; Watson 2021). Proteins from canola seeds used in sports beverages and frozen desserts exhibit good emulsification properties and improve colour and consistency (Watson 2022b). The oil extracted from rapeseed, sunflower and palm is used by industries to produce plant-based butter and margarine. Alternative or vegan cheese has also been produced from cashew and macadamia nuts oil while starch is often added to make hard cheese (gouda) when needed (Southey 2022c).

Food waste materials

Every year, billions of dollars are lost in countries all over the world as a result of food waste. For instance, about 3.5 billion tons of peel waste is generated from bananas annually. Banana peels contain a considerable amount of carbon compounds that decompose to generate volatile odoriferous compounds, GHGs and which therefore contribute to adverse climate change events (Ewing-Chow 2022). The peels also contain proteins, dietary fibre, polyunsaturated fatty acids, calcium and vitamin A (Ewing-Chow 2022), as well as antioxidants such as carotenoids and polyphenolic compounds. Banana peels have also been used for ethanol production and as a primary material for pectin extraction (Shalini 2015). Whole banana peel and flour can be incorporated into bread, tea, dried snacks (with peels) and bacon alternatives to increase their nutritional value (Martins et al. 2019; Wells 2021).

Due to its ability to foam, gelate, thicken, and emulsify foods, aquafaba (spent liquid from cooked chickpea) has caught the interest of vegans and those who design culinary products. It is stable over a wide range of pH and temperature conditions and is very process tolerant. In addition, aquafaba contains no fat and starch, thus making it different from protein isolate and chickpea flour. Instead, it is a diluted solution that contains soluble polysaccharides, phenolic compounds, saponins, low molecular weight, and water-soluble proteins (mainly albumin) (Mustafa & Reaney 2020). The main organic waste products from food production include seeds, peels, bracts, leaves, roots, bark, and midribs. Numerous bioactive substances including phytochemicals with nutritional and functional value can potentially be found in these waste products. For instance, the peels of pineapples contain about 222—428 mg GAE/100 g DW phenolics and can be used for several functionalities in processed foods including substrates for single-cell proteins, prebiotics, anti-browning agents, texture enhancers and as additives in new products (Pattnaik et al. 2021). Barley and wheat are present in spent grain, a by-product that is typically discarded following the mashing process in beer-making (Garcia-Garcia et al. 2019). Spent grains with about 11% protein and 12.7% carbohydrates and beer yeast can be used as feed for rearing insects such as mealworms to serve as an alternative protein source in human food (Mussato 2014; Varelas 2019), while cereal bran such as wheat and rice which are obtained after polishing rice are also extracted due to their amino acid content for use in food products.

Other alternative and emerging protein sources

The cell, clean or lab-grown meat concept involves the cultivation of animal cells to produce meat, outside the body of real animals, with similar sensory characteristics and nutritional profiles as the conventional meat (Innova Communcations 2021; Specht 2018; Swartz & Bomkamp 2020). Lab cultured meat and fish products have been developed to prevent the extinction of certain species, and produce meat with fewer antibiotics and microbial contamination (Rodriguez Fernandez 2022). To produce lab-cultured meat, the cells needed to cultivate the meat are obtained from healthy animals, grown in bioreactors or cultivators on nutrient-rich media including amino acids, vitamins, inorganic salts and other supplements (Swartz & Bomkamp 2020). The nutrient medium fed to the system is varied and this differentiates the cells into various muscles, fat and tissues as seen in meat. This process is usually completed within 2–8 weeks, depending on the meat of interest (Swartz & Bomkamp 2020). In fact, foods such as ground beef, steak, pork and poultry, sausage, fish and egg white have been produced by the food industry using cell culture (Rodriguez Fernandez 2019). Results from Szejda et al. (2021) in their study to determine the acceptance rate of cell-cultured meat in the US and UK showed that about 40%, 10% and 25—30% of consumers are eager to try cultured meat, willing to spend more on cultured meat, and make regular purchases, respectively. Consumers also revealed that cultured meat with Food and Drug Authority (FDA) or United States Department of Food and Agriculture (USDA) approval, and which are non-genetically modified will be preferred and should be labelled cultivated or cultured meat instead of cell-based meat. The cultivated meat concept is still in its infant stages and has a huge potential for growth depending on full consumer acceptability and the establishment of adequate regulatory standards for their production.

Given the continuing rise in global population, demand for seafood could double by 2050, thus highlighting the necessity for research into alternative seafood production using methods such as fermentation technology. However, seafood has varied and unique flavour profiles with respect to each fish type hence the difficulty in mimicking them. Thus, to create desirable seafood products, culinary and sensory needs must be aligned with scientific and technological realities in order to develop 'whole cut' products (Southey, 2022b).

Insect protein is also growing in popularity. Insects contain proteins, mono- and polyunsaturated fats, minerals (about 17% of zinc and 25% of iron) and some vitamins (Van Huis 2015). The profit from insect protein was $249.9 million in 2020 and is projected to continue to rise annually by a compound rate of 27.4% from 2021 to 2028 (Grand View Research 2022). The interest in insects as a novel protein source especially in the US, U.K, France, Germany, Thailand, India, South Africa, and Kenya is due to the high demand for alternative proteins (De Castro et al. 2018; Grand view research 2022; Leblanc 2019). Insects contain peptides with antihypertensive, antimicrobial and antioxidant properties, and can be used in food applications (De Castro et al. 2018). Insects are consumed as food and used as livestock feed in most parts of the world where they are obtained from the wild or forest population (De Castro et al. 2018; Salter 2019; Van Huis 2015). Insects are efficient feed converters with minimal dependence on water for their survival (Griopro 2016; Van Huis 2015). They are poikilothermic, with no body fat and are able to conserve water due to their tough exoskeleton (Griopro 2016). Their production requires less land and pesticide use. For bulk production, insects are reared in automated systems as mini-livestock (Van Huis 2015). The insect order Coleoptera (beetles, aquatic beetles, wood-boring larvae, and dung beetles), Orthoptera (locusts, grasshoppers, crickets) and Lepidoptera (caterpillars, butterflies, and moths) are widely used in insect-based oil, protein powder, and flour because they contain high amounts of protein and are easy to breed (Grand view research 2022). Fish food, beverages, protein bars and pharmaceuticals can also be formulated using insect proteins (Grand View Research 2022). Protein isolate made from *Gryllodes sigillatus* was reported to have high foaming capacity and stability of 99% and 92%, while *Schistocerca gregaria* and *Tenebrio molitor*, had an emulsion stability of 51.31 and 50.40 respectively, making them suitable to be incorporated into food (Zielińska et al. 2018).

Plant-based foods and alternative protein products

A sustainable diet, as defined by the Food and Agriculture Organization (FAO) must be safe, healthy, have sufficient nutrients and low environmental impact (Askew 2022b). Meat, egg, dairy products, bakery products (snacks), beverages, and dietary supplements have been developed from plant and alternative protein sources (Bunge 2022). The traditional source of these products, for instance cheese, has unique characteristics which confer distinct taste and flavour. For alternative cheese, producers must observe and take note of the interactions between ingredients, processing methods effects, proportion and various formulations, for easy replication and optimization (Edlong 2022). In plant-based meat products, the common characteristics consumers expect are taste/flavour intensity, texture (firmness and hardness), and nutritional value (Griffith foods 2020).

Plant-based meat (PBMs)

PBM is produced to mimic meat not only for vegetarians but for 'meat lovers' or flexitarians (Bellone et al. 2022; Clayton & Specht 2021). The production of PBM involves analysing and selecting appropriate plants and other raw materials (Allen 2018). Modified legume protein isolates for example, processed using hydrostatic pressure technology when included in PBMs improve functional properties during the product formulation process (Clayton & Specht 2021; Mulla et al. 2022; Semba et al. 2021). A combination of legumes e.g., pea and oat protein will not only add to the required protein content (60–70%) for good texture in extruded meat products but will also improve the amino acid profile, wettability, and stability over a wide temperature range (Lantmännen 2022). The hardness and dryness of alternate meat products, however, increase as the percentage of oat protein in the formulation increases (Lantmännen 2022). Other nutrients such as starch, fats, and additives such as lecithin are added to improve the sensory characteristics of PBMs. Burger formulations which include lecithin are juicier and tastier, uniformly brown and sizzle when baked compared to those produced without lecithin (Croklaan 2022), while the commercial citrus fibre, Herbacel, has been reported to improve final product texture and freeze–thaw stability, and also minimizes cooking and frying loss (Herbafood 2022).

In order to obtain the desirable fibrous nature of meat, plant proteins are texturized through shearing, extrusion and spinning. The temperature involved in the extrusion process accounts for the structural and chemical changes in plant protein to improve their functionality in the PBM products (Krintiras et al. 2016). The characteristics and cost of PBM can be improved by substituting cell-cultured fat into pure cultured PBM products (Rubio et al. 2020). For instance, cell-cultured pork fat from Mission Barns is incorporated into the hybrid pork alternative from Herotein to improve the taste as well as to subsidise production cost (Neo 2021). Other producers such as Better meat and Tyson foods in order not to lose the market to PBM industries blend meat products with plant-based ingredients to produce hybrid (50/50) products which taste better and have reduced environmental impact than 100% meat (Hill 2021).

Plant-based dairy products

About 7.4% of the market for milk is occupied by plant-based dairy alternatives (Laila et al. 2021; Schiano et al. 2020) and this is likely to rise by 8.8% between 2021 and 2031 (Southey 2022d). Plant-based dairy products contain milk sourced from legumes (soy, lupine chickpea), nuts (coconut, hazel), seeds (sunflower, hemp), pseudo cereals (quinoa), and cereals (oat), and have distinct flavours (Tangyu et al. 2019). It has been argued that milk from plant sources should be diversified in order to obtain maximum nutritional benefits and to prevent exploitation of the market for a particular product (Marinova & Bogueva 2020).

The lactose-free property of plant-based dairy products is of interest to many lactose-intolerant consumers (Laila et al. 2021). A recent survey conducted by Cargill revealed that 20% of consumers opted for plant-based dairy products to support animal life conservation (Loria 2018). Another study in Canada revealed that most parents recommended the use of plant-based dairy because they do not contain antibiotics and hormones which can affect the health of their children (Laila et al. 2021). Other reasons for the increase in the non-dairy industry are scarcity of bovine-derived milk in some areas, as well as low cholesterol levels and high bioactive phytochemicals of plant-based milk (Paul et al. 2019). The plant-based dairy industry seeks to produce milk with organoleptic and nutritional properties similar to conventional milk. In the manufacturing of non-dairy milk, milk extract from the desired plant source is combined with other ingredients such as oil, additives (enzyme deactivators), emulsifiers, thickeners (locust bean gum), flavours, preservatives and nutrients (tricalcium phosphate), before being filtered, sterilized and properly homogenised to prevent separation over time (Aydar et al. 2020; Mcclements 2020). Some examples of commercial plant-based dairy products currently available to consumers include cheese, milk and yoghurt (Ganeshram 2021; Veganuary 2022). A commercial plant-based powdered milk which was produced with the intention of reducing the weight of the final product for convenience and which consumers only need to dissolve in water as needed, is also currently available to consumers (Southey 2022d).

Production methods and innovations in formulation

Several methods and innovations including blending, cell culture, precision fermentation (PF), and genetic engineering have been explored in the manufacture of PBFs. Most PBF producers mimic the sensory properties and nutritional characteristics of conventional protein sources to attract consumers and obtain a wider market beyond vegetarians (Nwachukwu & Aluko 2021). In Table 1, some PBF producers, products and target for sustainability are shown.

Fermentation is a convenient, adaptable, technology that preserves food, increases shelf life, enhances nutritional quality, and has been used for developing new products with improved organoleptic properties (Teng et al. 2021). Chai et al. (2020), described the use of fermentation to transform substrates into value-added products such as enzymes, peptides, probiotics and other biotechnological products using endogenous microbes, starter culture or a portion of a previously fermented product. PF is one of the newest and major technologies used to produce PBFs where microbes are redesigned to produce specific, customised and recombinant molecules to yield new food ingredients. The goal of PF is to produce newer protein sources with desirable textural and taste characteristics for increased consumer acceptance (Vanhercke & Colgrave 2022). It targets the microbial genome where genetic information of specific proteins is modified.

Other technologies used in the production of PBM through cell culture include tissue engineering, and cell-based therapeutics (Specht 2018). Extrusion is another processing technique used for commercial production of PBFs where all ingredients are mixed, preconditioned, cooked, and extruded through dies (Moses 2022). Based on the company's product specifications, the extruded product is subjected to further processes including trimming, marinating and grinding.

Barriers/limitations to adoption of plant-based foods

Though PBFs patterns were associated with better consumer and environmental health, and people are being encouraged to consume more PBFs, their impact vary greatly. For instance, the higher scores for unhealthy plant-based diet index were associated with higher consumption of unhealthy plant-based diet such as refined grains, sugary drinks, fruit juice, potatoes, and sweets/desserts (Musicus et al. 2022).

Some plant-based ingredients such as legumes and cereals contain varying amounts of anti-nutrients such as phytates, saponins, tannins, protease and amylase inhibitors, and goitrogens that limit the amount of the ingredient that can be used in formulation due to their ability to form complexes with proteins and minerals reducing protein digestibility and overall nutritional quality, inhibit mineral absorption, cause stomach discomfort, and toxic when accumulated (Acquah et al. 2021; Samtiya et al. 2020). To minimize anti-nutrient content and cooking time, pulses are mostly soaked for several hours, however this may be inconvenient for some consumers (Szczebyło et al. 2020). The poor bioavailability of certain minerals (e.g., calcium, zinc, iron and iodine) and low content of vitamins (A, B2, B12, and D) has necessitated critical examination of PBFs and the inclusion of supplementary/alternative sources of these nutrients (Protudjer & Mikkelsen 2020).

Table 1 PBF industries, products and sustainability goals

Company	Location	Product/name	Ingredients	Production	Target	References
Impact food Finless food	Emeryville, California, U.S	Seafood (tuna)	Pea protein isolate, starch, algae	Blending and Cell culturing	Prevent overfishing and blue fin species extinction Zero- food waste	Crawford 2022; Watson 2022c
Merit food	Manitoba, Canada	Puratein Canola protein and pea protein	Canola seeds	Proprietary extraction and membrane filtration	Reduced environmental impact, uses less water	Merit Functional foods 2022a, 2022b
NotCo	Santiago, Chile	Not burger Not Milk	Notblood, Notmatrix, pea protein, pineapple cabbage and seeds	Artificial intelligence (Giuseppe) generates plant combinations followed by blending ingredients	Low carbon and water footprint. Minimizes pressure on land and energy usage	Watson 2022b
Perfeggt Egg	Germany	Alternative Egg	Fava beans	Not available	Uses 5% fresh water, emits 25.7% GHG and less land use	Southey 2021
Helaina	New York, U.S	Infant formula (breast milk alternative)	Yeast	PF	Production method with a low environmental footprint	Marston 2022
Nepra food	Chile	Propasta, Hemp seed flour (N-50), Cheese	Hemp seeds	Cold press, mill and blend hemp meal with other ingredients	Uses less land, water and energy resources to produce hemp seed	Accesswire, 2022a; Nepra Foods 2022a, 2022b
Ynsects	Paris, France	Protein powder for feed (Ynmeal) and food (Adalba Pro)	Molitor larvae (feed) and buffalo meal worm (food)	Proprietary technology	Low carbon emission and land use	Grand view research, 2022; Ynsect 2022
Veg of Lund	Sweden	Dug potato milk	Pea protein, rapeseed oil, emulsifiers and chicory fibre	Blending	About 75% lower climate footprint, minimized water and land usage	Synergy foods 2022; Anay 2021
Current food	San Francisco, U.S	Kuleana	Radish, bamboo, algae, potato	Proprietary (scaffolding) technology	Restore the ocean, no planet strain	Buxton 2022; Shieber 2020
Hooray foods	San Francisco, U.S	Bacon alternative	Rice flour and cassava	Encapsulation of fats and other ingredient	Combat climate change, prevent animal mishandling and slaughtering	Lyra 2021; Wilder 2021
Herotein	China	Hybrid beef and pork products	Soy, pea and wheat and cell cultured fats	Muscle fibre simulation technique and cell culture	Low environmental impact	Neo 2021
Spero	San Jose, U.S	Egg and cream cheese alternative	Sunflower (cheese) seeds, pumpkin seeds (egg) mushroom extract	Not available	Uses 96% and 99% less land and CO_2 emission for production compared to nuts and dairy, respectively	Watson 2021; Spero Foods 2022a, 2022b
Impossible food	California, U.S	Burger, sausage and chicken-like nuggets	Soybean and potato	Genetic engineering using yeast	Conserve water, save wildlife and reduce GHG emission footprint	Morrison 2021
Roslin Technologies	UK	Cultivated meat	Animal stem cells	Advanced cell technology	Conserve animal life and prevent negative environmental impact due to animal production	Roslin Technologies 2022

A poorly formulated PBFs using legumes with low non-heme iron content and absorption compared to meat requires that consumers eat more to meet the iron requirement (Semba et al. 2021). Consuming high levels of heme raises body iron content and increases the risk of type-2 diabetes (Zheng et al. 2019). For instance, commercial meatless burgers contain high amounts of sodium (16—17%) and heme (20—25%) per serving (Beyond Meat 2022; Zheng et al. 2019).

For people with food allergies, navigating diets that also minimizes nutritional deficiencies can be challenging. With about 467 allergens from certain PBF sources and about 436 being allocated to specific food protein families including 2S albumin, non-specific lipid transfer proteins, legumins, cereal prolamins, and profilins (Costa et al. 2022), greater attention is warranted by consumers with food allergies. Among the 170 foods that have been found to trigger allergenic reactions in the US, peanut, tree nut, wheat and soy are predominant, as well as some cross-reactivity between plant-based sources. Sesame seeds, lupines, mustard, buckwheat, gluten from wheat and soy protein have also been associated with allergenic reactions in other parts of the world (Bresciani & Marti 2019; Hertzler et al. 2020). Allergic responses happen when the immune system targets and attacks typically safe dietary proteins, causing temporary to severe and life-threatening symptoms (Hertzler et al. 2020). Consumers may consider other nuts, cereals and legumes as alternatives (Protudjer & Mikkelsen 2020). The use of precautionary allergen labelling is strongly encouraged.

Another potential PBFs pitfall is the susceptibility to aflatoxin invasion, favism and high alkaloid contents in peanuts, fava beans and lupins, strong beany flavour, extended processing time and lack of standardized techniques minimise the consumption of legumes (Acquah et al. 2021; Semba et al. 2021).

The processing of many traditional vegetarian dishes (tofu) requires less oil and salt. However, some plant-based burgers and sausages available in the market contain more salt and saturated fats (SF), leading to increased calories and salt content when consumed (Tso & Forde 2021). Some consumers have also expressed concerns that plant-based dairy products are costly, not readily available in the supermarkets and that some have high sugar content which can affect oral health (Aydar et al. 2020; Laila et al. 2021). Excessive use of sugar and salt to mask undesirable characteristics in plant-based products might limit its intake since the main reason for the switch to these products is for health benefits (Pratt 2020). It is recommended that the diet consumed per day should contribute 200 cal or less (5—6%) SF out of the 2000 cal needed (American Heart Association, 2021). The FDA also recommends the consumption of < 10% (239 kilo calories) SF per day at age 2 or older, 18 mg iron and < 2300 mg of sodium (Na) (U.S Department of Agriculture 2020). In Table 2, the nutrient composition of some plant-based products is presented.

In addition, the media used for culturing meat are mostly sourced from the fetal blood of a slaughtered pregnant cow which makes it expensive and at odds with the stance of animal welfare/rights groups (Rodriguez Fernandez 2022).

PBMs have organoleptic properties which are very different from conventional meat, are costly, and often come with unfamiliar ingredients on product labels (Morrison 2022). Additionally, alternative cheese is costlier with less nutritional value (Southey 2022c), while some plant-based milk produced from nuts such as almonds requires a lot of water during production (Southey 2022d).

Most consumers view PF as an unnatural and synthetic process that is directly linked to genetically engineered/modified (GM) foods which are seen by some consumers as a threat to human health (Teng et al. 2021). People seeking PBFs expect foods made from real plants due to cultural or personal reasons or otherwise considered "modified/unnatural". Food engineered through PF also has "ill-disposed" labels such as 'nature identical', and 'precision fermentation' with no explicit information on the content of the food (Bellingham 2022) which raises doubts about their consumption. Aside from the substantial increase in yield and final product purity, there is no distinction between naturally produced foods and those synthesized through GM technology (Teng et al. 2021).

Many consumers are uncomfortable and largely unenthusiastic about consuming insects (Leblanc 2019). Lastly, lack of convenience for meatless meals, limited options to choose from, and negative reactions by other consumers also serve as a barrier to the consumption of PBFs (Graça et al. 2019).

Regulations and safety concerns

PBFs are mostly displayed next to traditional products in most supermarkets. Product label captures consumers' attention and must be informative to avoid misleading them. It is expected that the FDA will present a draft label guidance for PBF products based on consumers' understanding of the distinction between PBF terms and nutritional composition from conventional products (Glick 2022). The type and major ingredient/composition must be clearly identified on the label with health claims thoroughly reviewed by FDA (Glick 2022). Producers should also include the score on animal welfare, water and carbon footprint on their labels (Southey 2022d). Recently, France banned the use of terms used to describe traditional meat such as meat, steak and bacon

Table 2 Nutrient composition of PBFs and FDA recommended daily intake of nutrients

DV*	PBF	Amount of Nutrient (%) per serving	References
Total fat (TF) (78 g) SF (20 g) Total carbohydrate (275 g) Dietary fiber (28 g) Sodium (2300 mg) Potassium (4700 mg)	Impossible beef burger	Na – 16 SF – 16 Fe – 25 TF – 18 Total Carbohydrates – 3 Potassium – 15	Link 2022
	Sweet Earth Burritos	Na – 24 SF – 35 Fe – 10 TF – 23 Total carbohydrate – 17 Potassium – 6	Sweet Earth 2022
	Morning Star Vegan Cheese Burger	Na -27 SF – 20 Fe – 10 TF – 23 Total Carbohydrates – 4 Potassium – 4	MorningStar Farms 2022
	Violife parmesan cheese	Na – 17 SF – 23 TF – 8 Total Carbohydrates – 3 Potassium- 0	MyFoodDiary 2022
	Pepita Eggs	Na – 69 SF – 24 Fe – 20 TF – 17 Total Carbohydrates – 1 Potassium – 4	MyFitnessPal 2022

Based on a 2000-cal daily diet

for PBF product to prevent confusion among consumers (Askew 2022a).

Conventional protein sources have been widely studied in contrast to plant-based protein sources and their alternatives (Boler & Woerner 2017; Małecki et al. 2021; Salter 2019). PBF are highly susceptible to microbial load than animal-based products due to the varied ingredients and macronutrients which are combined in formulating them (Engstrom 2021). PBFs must be carefully handled and monitored during production and safety regulations should be set to govern their use to satisfy consumers' quality demands. Rules regarding storage for PBFs should be properly established and the right cooking temperatures necessary to eliminate microbes must be set. Luchansky et al. (2020) reported that the 62.8 °C—73.9 °C minimum cooking temperature set by USDA for animal-based meat also reduced salmonella, and *Listeria monocytogens* load in both beef and plant-based burger to the same level. In addition, insects reared on organic by-products are prone to contamination which might compromise their safety (Van Huis 2015).

Most manufacturers aim to upscale their products but the regulation for cell-based meat for instance has not been unfolded. While cell-based meat is currently being regulated in Europe under Novel Food Regulation, the US has not finalised the decision on which regulatory body (FDA or the USDA) should handle cell-cultured products (Robertson 2022). Producers are thus seeking directions from consultants for cell-cultured products to meet both FDA and USDA standards on good manufacturing practices, hygiene and hazard analysis critical control point (HACCP).

Improving characteristics of plant-based foods to increase patronage

The texture, taste and nutrition of PBFs should be equivalent to those of their animal-based counterparts in order to favorably compete and be fully accepted by consumers (Merit Functional). Other factors such as price and familiarity can affect the patronage of PBFs (Watson 2022c).

High antinutrient composition in PBFs may be minimized through pre-treatment procedures such as roasting, soaking, fermentation, sprouting, milling and removal of bran (Samtiya et al. 2020). Germinating legumes for example Bambara groundnut usually for three days minimizes antinutrients, improves protein and starch digestibility, enhances functional properties (pasting, water absorption capacity) and is recommended as a good pre-treatment method (Chinma et al. 2021). Genetic mutation can reduce the antinutrients to mineral acid ratio in legumes but such products must be processed with caution to minimize the leaching of nutrients for example when soaked or cooked (Hummel et al. 2020).

The fat component of plant-based meat products is usually sourced from coconut oil which has a low melting point (25%) as compared to beef fat (42—45%) (Watson 2022a). Coconut fat tends to leak out or melt quickly while cooking (decreasing juiciness), and it lacks the distinct flavour found in either pork, beef or mutton fat, therefore, requiring other food additives during processing to make it desirable. This challenge can be overcome by using microbes for example oleaginous fungi through genetic engineering to produce fats with characteristics similar to animal fats in plant-based meat products (Watson 2022a). The structure and fibrous nature of PBMs can be improved by incorporating fungi-based products and fermented foods to mimic whole-cut meat and seafood (Morrison 2022). Instead of producing PBFs to only mimic conventional sources with respect to sensory characteristics, producers should focus on increasing the nutrient composition of these products (Tso & Forde 2021) and providing a list of familiar ingredients on labels (Morrison 2022). In addition, further research should be done to develop products with reduced fat, sodium and sugar content which are major nutrition concerns.

The prolamin technology developed by Motif Food Works in partnership with scientists from the University of Guelph uses corn to make plant-based cheese with increased springiness (Cumbers 2021). In the extrudable fat technology, fat is passed through an extruder and mixed with plant protein to develop a final product with a marbling effect as seen in meat (Cumbers 2021). Beyond Meat has recently introduced a new burger with less fat (35%) (Synergy foods 2022). Approaches such as improving existing products based on consumers' feedback when adopted by PBF manufacturers will help to maintain the industry.

The acceptance of plant-based milk will increase if they are formulated to have similar functional properties which include foaming and stability in beverages and structure, as conventional milk with no beany flavour. The beany flavour in soy milk may be eliminated through processing. Substituting non-dairy milk for conventional milk in products will be easier. To improve non-dairy milk, the natural structure of the plant sources which will be used should be disintegrated and other plant-based ingredients such as oils and emulsifiers should be added to create that colloidal effect which is a reason for the desirable attributes of dairy milk (Mcclements 2020).

Conclusion and future perspective

The benefits associated with the consumption of PBF and increasing demand have attracted a lot of consumer interest and incentivized entrepreneurs to venture into PBF businesses. Knowing the barriers associated with adopting PBFs and improving the characteristics based on these limitations will help increase the patronage of PBFs. A change in the current dietary pattern for PBFs is encouraged to minimize the contribution of animal-based products to climate change. The nascent nature of entomophagy and the novelty of the plant-based food industry require constant research and development (R&D) to improve product characteristics and consumer acceptance.

Plant-based ingredients must be diversified to increase repeat purchases and patronage and improve functionality in developing products. The growth conditions of these ingredients influence the sustainability of the final product. Growing and supplying these ingredients at the local or grassroots level will minimize the emission associated with transportation while bringing consumers closer to ingredient sources hence satisfying their need for transparency (Askew 2022b). For this reason, some companies have introduced blockchain technology, where all the company's information is kept and made accessible to consumers to promote transparency (Askew 2022b).

Overall, current evidence suggests that PBFs are a better and more viable alternative to animal proteins as they confer health benefits, use fewer production resources, and produce comparably more sustainable processing methods and techniques.

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Author details
[1]College Agriculture, Science and Technology, Department of Human Ecology (Food Science and Biotechnology Program), Delaware State University, Dover, DE 19901, USA. [2]Center for Nutrition and Healthy Lifestyles, School of Public Health, Loma Linda University, Loma Linda, CA 92350, USA.

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