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Review

Current Status and Economic Prospects of Alternative Protein Sources for the Food Industry

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Abstract: The rising demand for novel and alternative protein (AP) sources has transformed both the marketplace and the food industry. This solid trend is driven by social awareness about environmental sustainability, fair food production practices, affordability, and pursuit of high-quality nutritional sources. This short review provides an overview of key aspects of promising AP sources (plants, algae, insects, fungi and cultured protein) as well as the economic potential, prospects, and operational challenges of this market. The low environmental performance of livestock production, associated with high GHG emissions and land use, can be overcome by less resource-intensive AP production. However, despite the forecasted expansion and improved economic viability, key challenges such as regulatory concerns, consumer acceptance and product functionality still need to be addressed. While the consumption and production of plant-based products are relatively well established, research and development efforts are needed to remediate the main commercialization and manufacturing issues of unprecedented protein sources such as cultured protein and the emerging edible insects sector.

Keywords: global food chain; food production; market trends; sustainability; protein-rich products

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1. Introduction

Protein intake is commonly associated with animal-derived foods such as meat, shellfish, fish, dairy products, and eggs. These traditional protein sources cover general nutritional requirements and have been the most produced and consumed throughout history (Aiking & de Boer, 2020) [1]. However, there is an increasing social awareness about food production, adequate nutrition, and environmental sustainability. The greenhouse gases (GHG) emissions associated to agriculture, forestry and other land uses have doubled in the last 50 years (Deprá et al., 2022; Shabir et al., 2023) [2,3], but the current resource-intensive food production model still does not provide adequate nutrition to around 3.37 billion people (Amato et al., 2023; Cucurachi et al., 2019; UN, 2023a) [4–6]. In addition, solid evidence has shown that high intake of animal protein is associated with higher risk of cardiovascular disease, diabetes, and mortality (Hemler & Hu, 2019) [7]. Moreover, ethical concerns towards animal production could also stifle demand in the Western world (Grahl et al., 2020) [8]. Pressing issues about the sustainability of food production are expressed in the United Nations Sustainable Development Goals (UN SDG), which highlights concerns related to food security, clean water supply, responsible consumption, and production, among others (UN, 2023b) [9].

This scenario stimulates consumer interest for alternative protein (AP) sources as a way of providing sustainable, affordable, and nutritional options to replace or partially substitute for current mainstream food products (Amato et al., 2023; Bashi et al., 2019;

Grossmann & Weiss, 2021) [4,10,11]. Also, a significant portion of the population is now more inclined to adopt vegetarian, flexitarian and vegan diets (Kent et al., 2022) [12]. As a result, this shift in consumer demand is the biggest traction in the market now. The current AP market, estimated to be around USD 2.2 bn, is expected to continue growing to reach a market size of more than USD 150 bn by 2030 (Figure 1). The steep sales growth tendency of meat-free products and on market value of plant-based food companies point to a consumer market that is willing to cross the bridge from traditional animal-protein oriented diets into AP-rich diets (Talwar et al., 2024) [13].

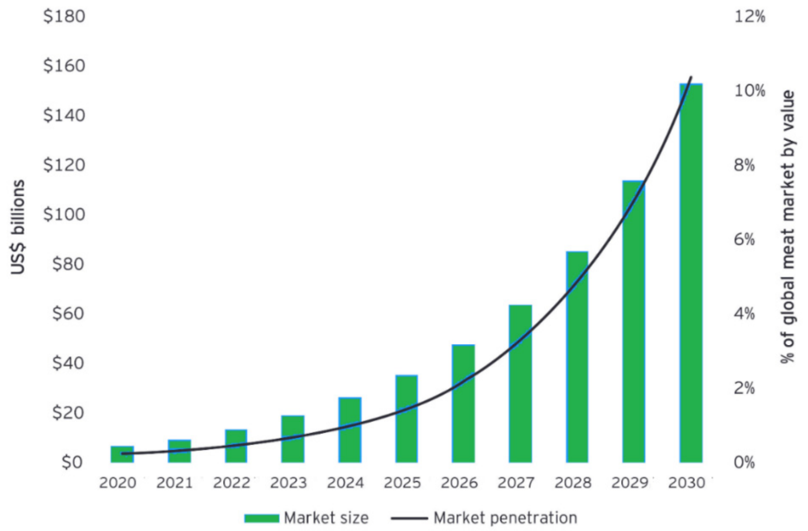

Figure 1. Projection of alternative protein market growth. Adapted from EY Parthenon Analysis (2021) [14].

Although opportunities for AP sources such as plants, insects and other novel protein sources have skyrocketed in both developing and advanced markets (Bashi et al., 2019; Lähteenmäki-Uutela et al., 2021) [10,15], studies have demonstrated the resistance of a significant share of the population to AP sources (Balfany et al., 2023) [16]. Food neophobia (the unwillingness to try new foods), and the sense of prejudiced disgust towards specific alternative protein sectors, such as insect-based and cultured proteins, have been identified as the two main factors hindering market growth (Siegrist & Hartmann, 2023; Wood & Tavan, 2022) [17,18]. Undesirable organoleptic attributes such as off-flavors and unpleasant texture, have also been raised as obstacles for the larger acceptance of AP (Malek & Umberger, 2023; Mancini & Antonioli, 2019) [19,20]. In this sense, the market interest has driven research and development towards overcoming these challenges and warranting wide access and acceptability of AP.

Therefore, this short review brings an overview of the fundamental aspects about the composition and applications of promising AP sources (plants, algae, insects, fungi and cultured), as well as the economic potential and perspectives of this emerging protein market. It also identifies key aspects of currently available technologies and foreseeable challenges in the future of alternative proteins.

2. Alternative Protein Sources

2.1. Plant-Based

Plant-based (PB) proteins are derived from vegetable sources, commonly legumes, grains, nuts, and seeds (Malek & Umberger, 2023) [19]. Among these, soybeans, peas, chickpeas, beans, rice, lentils and almonds are the most widely used (Gomes & Sobral, 2022) [21]. In addition, oilseeds are also regarded as potential sources since protein-rich meals (press cakes from oil extraction) are low-cost by-products from oil production (sunflower, rapeseed and sesame, for example), which can potentially be upcycled for protein production (Nicholson, 2022) [22]. PB proteins have rapidly become popular as the most readily available and easily accessible alternative to animal-based protein. Although animal-sources are usually perceived as the most common protein source, plant proteins account for an average of 60% of the global protein supply, with a significant geographic dependence, ranging from as low as 35% in Northern America, to as high as 84% in Western Africa (Roser et al., 2023) [23].

Protein profile and content are highly dependent not only on the PB source, but also on factors associated with plant growth conditions. Protein content in plant sources vary widely from as low as 2.9 g/100 g fresh weight (FW), for spinach and other green leaves, to 13.0–23 g/100 g FW, for common pulse sources such as peas and chickpeas (Balfany et al., 2023) [16]. Although proteins are a key part of human diet, the amount of protein ingested is not the only determinant influencing biological functions. Protein profile and digestibility also play a major role in the nutritional effects derived from protein intake. While animal-based protein sources, such as meat and eggs, have a complete profile of essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine), PB proteins usually lack select essential amino acids, which compromises their biological utilization (Maestri et al., 2016; Mariotti & Gardner, 2019; McCusker et al., 2014) [24–26]. Meat and eggs rank between 95–98% for digestibility, with a protein digestibility corrected amino acid score (PDCAAS) around 96–100%, while the digestibility of PB proteins is 97%, 89% and 64% for soybean, chickpea and kidney beans, with PDCAAS of 100%, 78% and 68%, respectively (Jiménez-Munoz et al., 2021; Kent et al., 2022) [12,27].

On the other hand, plant-based proteins have been associated with reduced allergenicity (when compared to dairy and eggs), and with biologically active peptides linked to enhancement of gastrointestinal health, and anti-hypertensive and anti-microbial activities (Balfany et al., 2023) [16]. For instance, buckwheat, beans and peas have bioactive peptides with in vitro anti-hypertensive activity, while potent antioxidant activity (both metal chelating and radical scavenging) has been attributed to cocoa, walnuts, rye and maize (McCusker et al., 2014; Samarakoon & Jeon, 2012; B. P. Singh et al., 2014) [26,28,29]. The combination of different sources of plant proteins and the use of PB products (flours, concentrates and isolates) is an efficient strategy to meet the recommended daily allowance (RDA) of protein and essential amino acid intake in animal-free diets.

Functionality and sensory performance of plant-based proteins are decisive factors for the use of AP for product development. Indeed, technological attributes such as emulsification, foaming and gelation capacities are essential aspects for processing and product development, although flavor and texture are still the biggest drivers for consumer acceptance of novel PB products (Ma et al., 2022) [30]. Functional attributes are related to physical and chemical properties that affect their interaction with other food components during product development, processing and storage (Akharume et al., 2021; Grossmann & Weiss, 2021; Jiménez-Munoz et al., 2021) [11,27,31]. Both intrinsic (protein content, amino acid profile, overall net charge, isoelectric point) and extrinsic (temperature, pressure, pH) factors govern the interaction between proteins and other molecules in food models (Pérez-Vila et al., 2022) [32]. Off-flavors, such as beany or grassy tastes, are usually perceived in PB proteins derived from pulses and green leaves, even after hydrolysis and concentration (Adámek et al., 2018; Mariotti & Gardner, 2019) [25,33]. While studies have shown that off-flavors might be related either with the binding of proteins to flavor-inducing molecules under processing conditions (usually pH and temperature) during isolation/concentration, or with the oxidation of polyunsaturated fatty-acids from the plant sources (Pérez-Vila et al., 2022) [32], product development strategies are usually necessary to either reduce or mask inherited flavors. Texture, on the other hand, is dependent not only on the protein technological attributes, but also on the overall food model characteristics. Wettability, water/oil adsorption, foaming, gelation and emulsification capacities, as well as the ability of the protein to maintain these attributes during storage, shape the textural properties of the proteins in food model systems. Studies have shown that process conditions such as temperature and pH have major impact on plant proteins solubility and, consequently, on their ability to interact with oil droplets, air bubbles and create stable films, for instance (Ma et al., 2022) [30].

The life cycle of plant-based proteins; however, is highly geographically dependent and influenced by national agricultural and transportation policies (Cucurachi et al., 2019) [5]. The technological development of high yielding crops, such as soybean and lentils, for example, is crucial for more efficient land use and water consumption (Shabir et al., 2023) [3]. Furthermore, technological development of crops and enhanced agricultural practices are expected to drive a significant change in the PB protein supply chain (Aimutis, 2022; Amato et al., 2023; Aschemann-Witzel et al., 2020) [34,35].

2.2. Algae

Algae-based protein sources are associated with seaweeds and microalgae and have gained increased attention in the food industry over the last decade (Gkarane et al., 2020) [36]. Both seaweeds and microalgae are photosynthetic, oxygen-producing organisms, but seaweeds are macroscopic, multicellular, marine species of algae, while microalgae are unicellular, microscopic forms. Algae species used for protein production are known to contain protein concentrations similar to animal-based sources such as meat, egg and milk (McCusker et al., 2014) [26], while delivering 4–30 times higher protein productivity, when compared to plant-based protein sources such as soybeans and pulses, and requiring far less resources (Thiviya et al., 2022) [37]. In fact, marine seaweeds, for example, do not require fresh water or arable land to grow (Birch et al., 2019; Rawiwan et al., 2022) [38,39].

Among seaweeds, brown, green and red algae are commonly used for human consumption, especially in East Asia. According to the Food and Agriculture Organization of the United Nations (FAO, 2023) [40], the Republic of Korea is the largest consumer market of algae, followed by China and Japan. High-protein seaweed species such as *Undaria pinnatifida* (brown algae, 24 g protein/100 g dry weight), *Ulva lactuca* (green algae, 32.7 g/100 g DW) and *Porphyra* spp. (red algae, 50 g/100 g DW) are considered promising candidates for alternative protein production. Among microalgae, *Arthrospira platensis*, also known as *Spirulina*, and *Chlorella vulgaris* are the most commonly cultivated species, with multiple applications as functional foods and generally regarded as safe (GRAS) both by the Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) (Lucakova et al., 2022; Thiviya et al., 2022; Wang et al., 2021) [37,41,42]. In addition to the relatively high protein content, algae-based protein is considered a favorable source of essential amino acids, comparable to eggs and soybeans (Eilam et al., 2023; Rawiwan et al., 2022) [39,43].

Given that the amino acid profile is highly dependent on species, growth parameters and phase, algae-based protein generally meets the essential amino acids standards. On the other hand, it has been associated with lower digestibility, when compared to traditional sources of plant-based and animal-based proteins (McCusker et al., 2014; Samarakoon & Jeon, 2012) [26,28]. De Bhowmick and Hayes (2022) [44] evaluated the in vitro digestibility of different species of seaweed and reported PDCAAS levels ranging from 8%, for *Fucus vesiculosus* (brown algae), to 69%, for *Palmaria palmata* (red algae). Among microalgae, the two most common species, *Spirulina* and *Chlorella* spp., are reported to present PDCAAS of around 77–84% (De Bhowmick & Hayes, 2022; Wang et al., 2021) [42,44]. However, the digestibility of algae protein is still poorly described in literature, since the shift of algae utilization as a source of proteins is relatively recent.

The technological attributes of algae-based proteins are comparable to traditional plant-based proteins, which contributes to their introduction in traditional food model systems (López-Pedrouso et al., 2020; Moura et al., 2022) [45,46]. Solubility, foaming, emulsification and gelation capacities, for example, have been found to be pH-dependent, which is also the case for most proteins from plant and animal sources, with a lower performance under acidic conditions closer to the isoelectric point, and favored under alkaline conditions, where the proximity to the pKa of amine groups favors solubility and decreases hydrophobic repulsion (Bleakley & Hayes, 2017; Gómez et al., 2019; Strauch & Lila, 2021) [47–49]. On the other hand, the presence of di- and trivalent cations, such as Ca^{2+} and Al^{3+}, can negatively affect the performance of both microalgae and algae-based proteins in food applications, since they can promote flocculation by ion bridging the usually negatively charged surfaces of algae-derived products (Gkarane et al., 2020; Gómez et al., 2019) [36,48].

2.3. Edible Insects

Insects have been historically consumed as part of the human diet for centuries, especially by African and Asian cultures (De Castro et al., 2018) [50]. Insect proteins have recently received increasing attention from an environmental perspective, especially for their efficient energy conversion to biomass that exceeds many livestock, which makes them produce protein more efficiently (Chéreau et al., 2016; Yi et al., 2013) [51,52]. Currently, over 2000 insect species have been identified as edible (Mishyna et al., 2021) [53] and commonly studied edible insects include mealworms (*Tenebrio molitor*), superworm (*Zophobas morio*), lesser mealworms (*Alphitobius diaperinus*), house crickets (*Acheta domesticus*), dubia roaches (*Blaptica dubia*), black soldier flies (*Hermetia ilucens*) and western honey bees (*Apis mellifera*). Edible insects show high protein content with suitable amino acid profiles and studies confirm that their nutritional profile is suitable according to FAO standards (FAO/WHO/UNU, 2007) [54]. On average, they have 40–75% protein by weight, on a dry basis (Verkerk et al., 2007) [55], including *A. domesticus* (32.6%), *T. molitor* (38.3%), beetles (42.2%) (Huang et al., 2019) [56], grasshoppers (61–77%) and butterflies (15–60%) (Verkerk et al., 2007) [55]. *H. ilucens* has a high content of essential aromatic amino acids (phenylalanine and tyrosine) and sulfur essential amino acids (methionine and cysteine). On the other hand, *T. molitor*, *Z. morio*, *A. diapernius*, *A. domesticus* and *B. dubia* were reported to be deficient in tryptophan, valine, isoleucine and threonine, three of which are essential amino acids (Yi et al., 2013) [52].

Industrial processing of edible insects mostly follows three main steps: pre-treatment, drying and formulation (Liang et al., 2024) [57]. Following harvest, pre-treatments generally intend to decrease microbial contamination and enzyme activity for the purpose of ensuring food safety and avoiding possible lipid oxidation (Laroche et al., 2019) [58]. Blanching and freezing are the most cited pre-treatment options applied to common insect protein sources (*Hermetia illucens*, *Tenebrio molitor*, *Acheta domesticus*), with blanching being featured as the most cost-effective (Singh et al., 2020; Yongkang et al., 2020) [59,60]. Drying is an important step for increasing the shelf-life of edible insects. Traditional solar drying has been replaced by industrially preferred convection oven drying. Freeze drying and microwave drying have also been investigated, but the high costs associated with equipment and operation hinder their wide implementation (Liang et al., 2024) [57]. Finally, the formulation step varies with the intended application of the insect-based product and it goes from simple grinding and bleaching, for the production of protein-rich insect flours, to alkaline protein extraction (protein-rich ingredients) or solvent-based solid-liquid extraction (insect oil or chitin production) (Liang et al., 2024) [57].

Reports on functionality of insect proteins vary with species and are scattered. Defatting is a common pre-treatment, and the choice of defatting solvent, as well as the choice of extraction procedure affect the solubility and functionality of insect protein (Queiroz et al., 2023) [61]. Mishyna et al. (2021) [53] demonstrated that protein concentrates of mealworm (*T. molitor*), cricket (*Gryllodes sigillatus*), and locust (*Schistocerca gregaria*) had water-holding capacity and oil-holding capacity up to 300% greater than their respective raw flours. *H. ilucens* was reported to have a great foaming capacity, increasing up to 1080% after thermal treatment (Queiroz et al., 2023) [61], while *A. mellifera* (Mishyna et al., 2019) [62], *A. domesticus*, *T. molitor*, *Z. morio*, *A. diaperinus*, *B. dubia* exhibited poor foaming properties (Yi et al., 2013) [52]. On the other hand, *A. domesticus* exhibited far better gelling properties than other insects (Queiroz et al., 2023) [61]. Due to the wide range of functionalities between species, insect protein needs to be screened for their functionalities before their use in food formulations.

Currently, there are two major challenges for the insect protein industry. Despite the history of consumption, insects are commonly deemed as dirty and unpleasant, which is a serious impediment for their commercialization (Alhujaili et al., 2023; Caparros Megido et al., 2016; De Castro et al., 2018) [50,63,64]. In addition, insect protein has been reported to negatively affect the sensory properties and certain physical properties when used as ingredients in either carbohydrate-based foods (pasta, cereal, bread) or animal food analogues (ice cream, sausage, jerky) (Kim et al., 2022) [65]. For example, current problems with *T. molitor* protein are the particle size and salt content, which affects the appearance, texture, and perceived coarseness (Wendin et al., 2019) [66] of the final product. Addition of *T. molitor* in biscuits led to negative sensory scores (Biró et al., 2020) [67]. Similarly, the use of cricket powder in protein bars and energy bars were associated with lower liking scores (Adámek et al., 2018) [33]. However, insect protein hydrolysates have shown promising results. The addition of cricket and locust protein hydrolysates significantly improved the sensory quality, microbiological characteristics and antioxidant properties of aged cheese and goat or sheep meat emulsions (Lone, Bhat, Aït-Kaddour, et al., 2023; Lone, Bhat, Kumar, et al., 2023; Singh et al., 2023) [68–70]. Reports on the incorporation of insect protein into food products are still incipient, but there is a pressing need to invest in research and development strategies to enable the offer of appealing insect-derived products in the market.

2.4. Cultured (Cell-Based) Protein

Cultured protein, also known as cell-based, in vitro or lab-grown protein, refers to protein products obtained from the cultivation of mammalian cells under controlled conditions (Mancini & Antonioli, 2019) [20]. Developed by the biopharmaceutical industry and usually implemented for monoclonal antibodies and vaccine production, the technology for mammalian cell cultivation has secured significant investments both from industry and academia, aiming to a rapid technological advance on protein production. However, this protein segment is still in its infancy, as the first patents and technical reports addressed this subject around the year 2000. In 2013, the first cultured beef was tasted in London (Hadi & Brightwell, 2021) [71].

Significant improvements in product quality and affordability have occurred along the last decade, from around USD 1.2 million per pound, in 2013, to around USD 50 per pound, in 2021 (Chriki & Hocquette, 2020; Specht, 2020) [72,73]. The process of producing cultured protein can be divided into four main steps: (1) The mammalian stem cells are harvested from an animal via biopsy, followed by mechanical and enzymatic digestion for isolation; (2) The cells are proliferated in a culture medium to increase the number/concentration of viable cells; (3) The cells are differentiated into skeletal muscle cells and fibers; (4) The cells can be assembled in scaffolding materials to deliver a final meat product (Post, 2014) [74].

Two main types of stem cells are considered suitable for protein production: skeletal muscle cells, also known as satellite cells, and embryonic stem cells (Bogliotti et al., 2018; Post et al., 2020) [75,76]. When satellite cells are used, the final product is composed only of skeletal muscle fibers and do not resemble the complexity of animal-based protein, which includes other components such as fat and connective tissue, leading to a decrease in consumer appeal and overall quality (Bryant & Barnett, 2020; Bryant & Sanctorum, 2021) [77,78]. A highly complex meat structure can be achieved with embryonic stem cells, which are able to be further differentiated into different tissues including intramuscular fat and connective tissues, via adipogenesis and fibrogenesis, respectively, and microvascular network, via vascularization (Ben-Arye & Levenberg, 2019) [79].

Considering that they come from mammalian cells, cultured protein is expected to deliver the same structure, taste, texture, and functionality of animal-based protein (Chriki & Hocquette, 2020; Mancini & Antonioli, 2019; Onwezen et al., 2021) [20,72,80]. Studies have shown that cultured protein digestibility scores high in the PDCAAS test (around

92%), with an amino acid balance comparable to beef. However, there is little information on the presence and bioavailability of minerals, such as iron, zinc and selenium, and vitamins, such as A, B12, D and E, commonly found in animal-sourced proteins (Hurrell & Egli, 2010) [81]. Consumer acceptance of cultured protein is still hampered by taste and texture, which are still far from being considered optimal, when directly compared to them by consumers (Bryant & Sanctorum, 2021) [78]. The food industry has targeted comminuted products such as burgers, minced beef and nuggets, for example, in order to overcome texture issues (Mancini & Antonioli, 2019; Onwezen et al., 2021) [20,80]. Furthermore, consumer preference studies have shown that the perception of "unnatural" production, coupled with concerns with food safety and proper production regulations, can generally lead to a sense of disgust and neophobia that increases consumer resistance to cultured meat proteins (Bryant & Barnett, 2020) [77].

Scalability and environmental performance remain the biggest challenges in the implementation of cultured protein (Specht, 2020) [73]. Because it involves unprecedented and yet to be established techniques, there is a lack of previous operational data and economically efficient cultivation protocols on a larger scale. Moreover, the high demand of resources, especially electricity and water use, influence both the production and the consumer acceptance, and still require improvement before cultured proteins get to the commercial level (Bashi et al., 2019) [10].

2.5. Fungi

Mushrooms have received renewed interest due to their nutritional properties and high protein content but especially for their sensory profile which is acceptable for their use in meat analogues (You et al., 2022) [82]. Their relatively simple production protocol using low value materials such as sawdust and branches (Okuda, 2022) [83] justifies why fungi-based proteins are a steep-growing trend in the food sector. Indeed, their estimated consumption exceeds 12.7 million tons (El-Ramady et al., 2022) [84]. The cost of industrial mushroom production can be as low as USD 0.026 per fresh kg, or even lower USD 0.014 cents per fresh kg, with optimized heating and cooling systems (Beghi et al., 2020) [85]. The growth period, depending on the species, can be as short as 42 days to produce 25,000 kg of fresh white button mushrooms (*A. bisporus*). The biological efficiency of converting growth substrate to mushroom biomass can be as high as 250%, which is an impressive efficiency compared to other crops where 80–90% of biomass is left unused after harvest (Chiu et al., 2000) [86].

Their high protein content (average 27.5% on a dry basis) and complete amino acid profile by FAO standards (Kalač, 2013) [87] differentiate them from most non-animal proteins. For instance, individual chemical scores of nine essential amino acids of three commonly consumed mushrooms (*Agaricus bisporus*, *Pleurotus ostreatus* and *Lentinus edodes*) satisfy the FAO standards (FAO/WHO/UNU, 2007) [54]. Additionally, evidence shows that mushroom protein has antioxidant activity (Goswami et al., 2021; Khongdetch et al., 2022) [88,89] and therapeutical properties (Bovi et al., 2013; De Mejía & Prisecaru, 2005; Ditamo et al., 2016) [90–92].

Despite these advantages, the incorporation of mushroom biomass or protein into food matrices, and their processing into protein concentrates and food ingredients are recent. Mushroom processing is generally divided into three main categories: (1) post-harvest processing for fresh market, (2) processing into convenient canned, sauces or pickled foods, and (3) extraction of high-value ingredients for functional and pharmaceutical applications (Zhang et al., 2021) [93]. While post-harvest processing focuses on drying and irradiation techniques to extend the shelf-life of fresh mushrooms (Barzee et al., 2021) [94], the use of mushroom-derived ingredients is more developed for high-end pharmaceutical applications.

As AP source, the use of mushrooms in meat analogues such as nuggets or patties is limited, but sensory acceptance has been positive when mushrooms were used as partial replacement (You et al., 2022) [82]. Alkaline extraction followed by isoelectric precipitation has been the only method tested so far for the extraction of mushroom protein aiming at the production of fungi-based protein concentrates. One interesting study analyzed proteins of 50 different mushrooms under the Osborne classification, based on protein solubility (Bauer Petrovska, 2001) [95]. Common culinary mushrooms such as white button mushrooms (*A. bisporus*), shitake mushrooms (*L. edodes*), and oyster mushrooms (*P. ostreatus)* contain only 20–30% globulin (salt-soluble) fraction. This contrasts with plant proteins that largely contain storage globulin proteins (Chéreau et al., 2016) [51], that favor protein production through isoelectric precipitation. On the contrary, protein fractions such as albumin (water soluble) are left unrecovered in the liquid phase during protein production (Yang et al., 2022) [96].

3. Economic Potential and Market Perspectives of Alternative Protein

3.1. Global Market

New products with protein-related claims ("high protein" or "source of protein") are increasing in Africa/Middle East (+41%), Europe (+26%), Asia (+15%), Australasia (+12%), Latin America (+8%), and North America (+2%), between 2018 and 2022 (Research and Markets, 2021a) [97]. The market value for AP reached USD 77.0 bn globally, in 2022, and it is expected to increase to USD 193.75 bn, by 2028. In the United States alone, the market value corresponded to about USD 1.1 bn, in 2020 (Vegconomist, 2021) [98] and it is expected to reach USD 10.1 bn, by 2027, with an annual growth rate of around 9.7% (Research and Markets, 2021a) [97]. Indeed, the North American market is the biggest sales share on this protein segment, followed by Europe (Figure 2A). Other relevant AP markets are China, Japan, and Canada, with a growth forecast of 9.5% (to reach USd 351.4 million), 7.1%, and 7.4%, respectively, from 2020 to 2027. In Europe, the German AP market is expected to grow approximately 7.3%, while the rest of the European market should reach USd 351.4 million, by 2027 (Albrecht, 2021) [99]. In terms of AP source, PB accounts should continue dominating the market up to 2029, followed by fungi-based and algae-based proteins (Figure 2B).

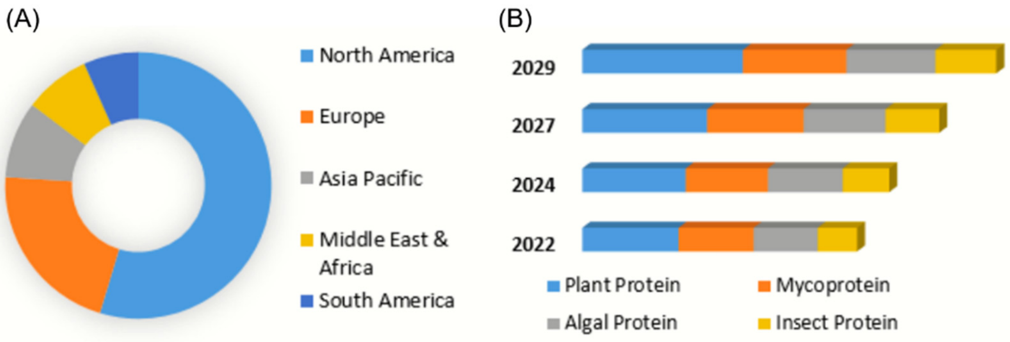

Figure 2. Global alternative protein market by (**A**) region and (**B**) protein source. Adapted from MMR (2023) [100].

The revolution resulting from the growth of AP market could lead to the generation of novel jobs in agriculture. Substitute foods might experience a new growth wave with technological advances such as data analytics, artificial intelligence, and biotechnology that enable the creation of new foods using 3D printers and other enhanced techniques (Knorr & Augustin, 2024; R. Singh et al., 2023) [70,101].

3.2. Plant-Based Protein

Different from other segments in the AP ecosystem, PB proteins are well known in the marketplace. Due to its historical presence, the sector lies on well-established regulatory grounds, and it is generally well accepted by consumers. In fact, the market demand for soy and wheat protein precedes the recent renewed interest for plant-based proteins. Together with rice, peas and chickpeas, they are now mainstream plant-based protein sources offered in the global marketplace (Aimutis, 2022) [34].

The market growth depends on the producers' ability to develop tasty, competitive, and versatile products. Functional foods and sports nutrition are major segments of the PB protein market share, and protein-rich powders, bars and ready-to-drink beverages are popular products in the United States (Figure 3). Moreover, the use of chickpeas, brown rice, fava bean and mung bean protein is growing significantly as egg substitutes. Lentil, wheat and flaxseed proteins are gaining popularity in products directed to athletic performance. Plant-based versions of much-loved animal-based products are now available in grocery stores. Food manufacturers, both small and large food companies worldwide, are investing in plant-based milk, eggs and meat substitutes. They are increasingly competitive among animal-derived products in terms of taste, price, and accessibility. AT Kearney predicts that by 2040, 60% of the consumed meat will come from alternative-sourced meat substitutes, 25% of which will be plant-based (AT Kearney, 2019) [102].

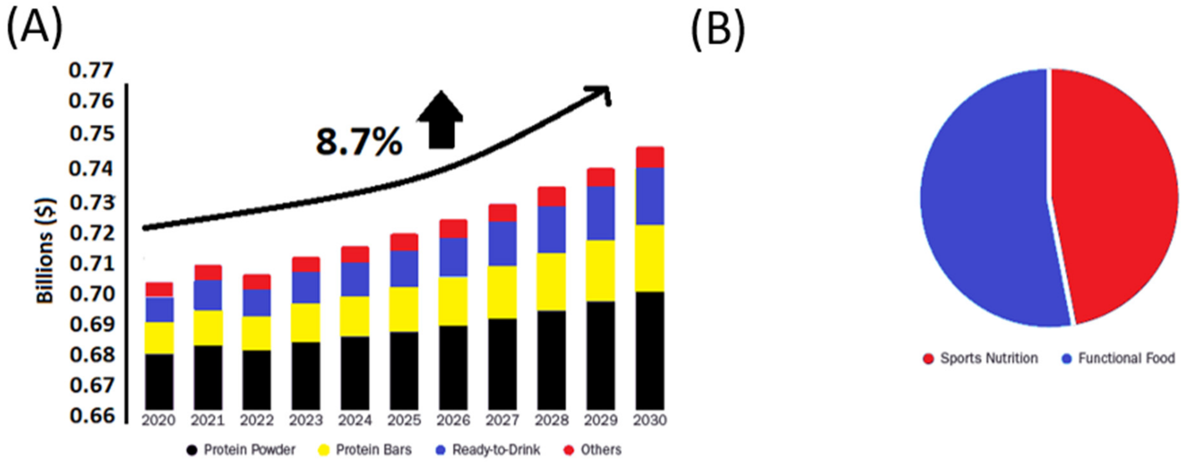

Figure 3. (**A**) US Plant-based protein supplement market, (**B**) Global plant-based protein supplement market share. Adapted from Grand View Research (2023) [103].

The plant-based milk segment is the most popular category among PB substitutes. The market associated with this segment is around USD 2.5 bn, and plant-based milk substitutes alone correspond to 35% of the total market size of PB foods. Refrigerated non-dairy milk makes up most sales in this segment, led by almond, oat, and soy milk. Oat milk, for example, has experienced massive growth in recent years, going from a small market segment in 2018 to becoming the second most demanded plant-based dairy product in 2020 (GFI, 2021) [104]. Although being a well-established market, some novel alternative milk products are now found on supermarket shelves such as banana milk and products produced with plant blends.

The growth of plant-based milk substitutes, which is currently purchased by 39% of American households has stimulated the growth of other plant-based dairy substitutes, such as ice cream, yogurt, butter, cheese, and eggs. Soy protein, one of the first leading ingredients heavily used for alternative products, has decreased at a compound annual growth rate (CAGR) of 6% from 2004 to 2019. Conversely, interest in pea protein grew at a CAGR of 30% during the same period (McKinsey, 2020) [10]. This trend is partly due to health concerns related to soy protein, such as allergenicity and estrogenic concerns. The total market value associated with these alternative products amounted to USD 1.9 bn, in 2020, and represents a combined sales growth of 28%, compared to 2019, and 55%, compared to 2018.

In 2020, PB meat substitutes reached a market value of USD 1.4 bn, representing an increase above USD 430 million in sales compared to the previous year and a sales growth of 45%, between 2019 and 2020. The best-selling format of PB meat substitutes are burgers, sausages, nuggets, tenders, and chops. PB refrigerated meat substitutes have been more available to the public in animal-based meat sections in supermarkets, rather than in aisles dedicated to vegan, organic, or special dietary needs. This alone reflects significant changes in both product innovation and marketing strategies.

Some interesting trends have been observed. For example, data shows that in the United States, 98% of people who buy plant-based meat substitutes also buy conventional meat (GFI, 2021) [104]. Products that try to replicate and emulate taste, texture, and appearance of animal meat dominate sales in this segment, in contrast to non-similar products such as black bean burgers and vegetarian hamburgers, whose sales are much lower. PB beef is the best-selling substitute in the meat substitute subcategory, followed by pork and chicken substitutes, but PB seafood (fish and shellfish) still needs competitive proposals in the United States market (GFI, 2021) [104].

3.3. Insect Protein

Entomophagy as a possible solution for food insecurity and sustainable diets has been studied and discussed for many years, but its actual implementation in Western societies is still incipient. On the contrary, this type of protein source has been present in Asian and African markets for a long time. The global market value for insect protein represented around US$ 144 million, in 2021, and it is expected to reach USD 1.33 bn by 2026, with a growth rate of 45.7% per year (Market Data Forecast, 2021) [105]. Other market forecasts; however, have more optimistic predictions. Barclays estimates that the insect protein industry could be worth USD 8.0 bn by 2030 (Barclays, 2021) [106]. World-leading food manufacturers such as Nestlé, PepsiCo and Tyson have started operations in this sector (PitchBook, 2021) [107], and restaurants, supermarkets, and even the Seattle Baseball Stadium are incorporating insect-based snacks.

Insect protein farming is less expensive than traditional animal protein sources (Market Research Future, 2021) [108]. Besides pursuing technological advances to enable a more efficient and appealing way to incorporate insect ingredients in traditional foods, and addressing organoleptic and functional issues, a lot needs to be done in the legislation arena. To take full advantage of the potential benefits of insect protein and expand markets, regulatory efforts are crucial. Extensive revisions of the food regulations are ongoing at this moment in several countries, and the future of the insect protein industry is highly dependent on this (Sogari et al., 2023) [109].

3.4. Cultured Meats

Actual cultured meat products are still not marketed in the United States and several other countries, which makes it difficult to build reliable market predictions. However, some agencies expect a market size of around USD 140 million, by 2030, and USD 630 million, by 2040, including 35% of the world's demand for meat (AT Kearney, 2019) [102]. Cultured meat is expected to be in restaurants in the next years as this production method is supposed to become cost-competitive in the next decade (Rabb, 2021) [110].

Optimistic growth prospects rely on the similarity of cultured meat to animal-sourced meat regarding sensory and nutritional attributes (Jeffries, 2019) [111]. On the other hand, high production costs, disputable consumer acceptance of cultured and genetically modified foods, and sanitary regulations are some of the reasons why any realistic market growth might only occur after 2030 (McKinsey, 2020) [10]. However, the recent marketing authorization obtained by Eat Just in Singapore for cultured chicken meat after a lengthy regulatory process could favor the approval of this type of meat in other countries (Poinski, 2021) [112]. In addition to meat grown for human consumption, there are companies dedicated to developing farmed seafood products and pet food.

3.5. Fungi Proteins

Mycofermentation has become the third technology pillar of the AP revolution in 2020. Fermentation has been used to produce foods and drinks for thousands of years, but 2020 became a landmark for mycoprotein production, due to the notable increased use of mycelia and mycoproteins (GFI, 2021) [104]. The global market for fermentation-based

AP is expected to reach USD 422.26 million, by 2026, with an annual growth rate of 5% between 2021 and 2026 (Research and Markets, 2021b) [113]. It is anticipated that the main factors driving the growth of this market are food allergies and intolerances associated to dairy protein, which have increased in recent years.

Fermented mycoproteins have a longer shelf life and environmental advantages, such as reduced organic waste production (Research and Markets, 2021b) [113], and fast processing time, since fermented protein can be obtained within a month through industrial fermentation (Research and Markets, 2021b) [113]. Furthermore, fungi fermentation costs are very moderate. To date, companies that have developed promising mycofermentation technologies are very young and need more financial and personal resources. On the other hand, a factor that could negatively affect the growth of mycoproteins is the regulatory requirements for manufacturers to label these products, including the term "mold", which does not have a positive connotation among consumers (GFI, 2021) [104].

4. Conclusions and Outlook

The high demand for AP sources has motivated both the mainstream food industry sector as well as new entrepreneurs to venture into this promising market. Current evidence suggests that they are a viable alternative to animal proteins as they confer health benefits, and use fewer natural resources, and comparably more environmentally friendly processing techniques. The PB protein market is relatively well-established, but new supply sources have been added to the industry portfolio to satisfy consumers avidness for novelty, convenience, and sustainability, without compromising sensory attributes and affordability. The forecast for the AP market predicts significant expansion and more competitive products in the near future. Algae protein-based products perform well in specific regional markets and show desirable high productivity with low resource input, making them promising candidates for market expansion. However, despite the optimistic scenario and large investment in this sector, key challenges still need to be addressed. Emerging protein sources such as insect protein and cultured meats need advanced research and development to improve product attributes and consumer acceptance. Moreover, regulatory issues and allergenicity concerns have yet to be solved. The food industry needs to be aware of the trends, challenges and opportunities taking place in the protein production arena. The AP market not only promises economic prosperity but also leads to a broad societal shift towards sustainable and ethical food production and consumption, and plays a pivotal role in the future of the global food industry.

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