Meat and Muscle Biology™

Meat Alternatives and Their Impact on Human Health: A Comprehensive Review

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Abstract: In the contemporary landscape, conventional meat faces increasing scrutiny due to recent allegations raised by various associations and scientific groups. While these criticisms are often linked to excessive meat consumption, a growing number of individuals are reducing or eliminating meat from their diets, questioning its role in a healthy diet. The consequent request for alternative protein sources has prompted the food industry to create so-called "meat alternatives" products. These emerging foods aim to replicate the sensory characteristics of conventional meat, eliminating the need to slaughter animals, and minimize environmental impact. Despite the misleading claims of various supporters, the long-term nutritional sustainability of these novel products remains unclear. To date, products resembling meat, which exploit different sources such as plants, algae, fungi, insects, and *in vitro*–cultured animal cells (cell-based food) require an unavoidable level of industrial processing, rendering the final products as ultra-processed foods (UPF). Given the well-established adverse effects associated with prolonged consumption of UPF, it raises questions about whether these products truly serve as a viable substitute for whole and unprocessed foods, like meat. With limited scientific knowledge and technological innovation to date, the long-term effects of meat alternatives on human health remain unclear. Addressing this crucial gap, together with guaranteeing transparency of research, should be a top priority for the food industry, guiding decisions on whether investment in these emerging food products is not only a cost-effective but also a health-conscious strategy.

Key words: meat alternatives, nutrition, protein sources, sustainability, long-term effects, ultra-processing
Meat and Muscle Biology 8(1): 17711, 1–19 (2024) **doi:10.22175/mmb.17711**
Submitted 5 February 2024 Accepted 24 April 2024

Introduction

Despite being a nutrient-dense food providing highly valuable amino acids and vital micronutrients (De Smet and Vossen, 2016), meat has become increasingly charged among some scientific communities and activist groups, who argue that meat consumption leads to various health, environmental, and ethical issues. Although such allegations have been associated with meat overconsumption rather than to its normal or moderate consumption (Smetana et al., 2023), consumers have started to decrease, or even eliminate, meat from their diet anyway, thus raising the demand for alternative protein sources (Vallikkadan et al., 2023). At the same time, however, it is important to specify that consumer attitudes toward livestock production and meat consumption cannot be generalized and should be always considered in relation to specific sociodemographic features, including population needs, cultural background, dietary habits, economic condition, etc. (Liu et al., 2023). The originated protein-market gap, in addition to sustainability concerns, have prompted many food industries to exploit different protein-rich sources to produce so-called "meat analogs." These novel products seek to provide consumers the same nutritional benefits and sensory properties of meat to reduce meat consumption while simultaneously improving dietary health and environmental sustainability. Meat analogs are part of the broader category of "meat alternatives," which includes any source of alternative protein that can be used to substitute meat without the need to mimic its nutritional and sensory traits (Smetana et al., 2023). Despite the promising claims related to these products, significant gaps in scientific and technological knowledge do not yet warrant establishing whether meat alternatives are more sustainable than meat (Siegrist and Hartmann, 2023; Smetana et al., 2023). According to the NOVA classification system, the ultra-processed food (UPF) category includes formulations generally composed of many cheap ingredients and additives, presenting high energy density and palatability, whose frequent consumption has been well-associated with an increased hazard of all-cause mortality (Bonaccio et al., 2022). The majority of meat alternatives fall into this category, and the paucity of clinical studies on their long-term consumption further increase the uncertainties concerning overall naturalness and sustainability, thus challenging the future market application of these novel products (Siegrist and Hartmann, 2023).

In the last decade, the literature on meat alternatives has grown exponentially, addressing a wide array of topics, including consumer acceptance (Onwezen et al., 2021), development status and technological challenges (Zhang et al., 2022), processing technologies, product formulations, chemistry and functionality (Sha and Xiong, 2020), and categorical similarities and differences between animal meat and alternative products from the perspective of structural and molecular standpoints (Xiong, 2023). Furthermore, a number of reviews provided integrated conceptual frameworks (Bonny et al., 2017; van der Weele et al., 2019; Lee et al., 2020; Gastaldello et al., 2022; Liu et al., 2022; Tyndall et al., 2022; Coffey et al., 2023; McClements, 2023, 2024) offering interesting multi-perspective approaches, sometimes also including nutritional features of meat alternatives, although lacking a specific focus on the nutritional sustainability of such products and not necessarily linking it to strict comparison with the nutritional quality of meat.

The scope of this review, instead, is to provide updated knowledge on the major protein-rich edible sources currently used in the production of meat alternatives, namely plants, algae, fungi, insects, and *in vitro*–cultured animal cells (cell-based food). The focus will be on their nutritional composition, which will be compared to that of meat, whose meaning and nutritional significance will also be briefly recalled. In addition, information about the sensory characteristics of such products will also be provided, when available, together with existing digestibility data, the latter being a key aspect to be considered in establishing the health value of a food product. The presence or absence of compounds potentially beneficial or hazardous for consumers will also be included. Lastly, a detailed analysis for each of the major protein-rich edible sources currently used in the production of meat alternatives will help to give an overall picture of the strengths, weaknesses, opportunities, and threats (SWOT) related to these products' nutritional sustainability.

Nutritional Role of Meat

Before delving into meat alternatives, a necessary starting point is to briefly recall what is meat and which is its role in human nutrition. Meat is defined as "skeletal muscle and its associated tissues derived from mammalian, avian, reptilian, amphibian, and aquatic species commonly harvested for human consumption" that underwent biochemical reactions linked to a postmortem condition, which converts muscle into meat (Boler and Woerner, 2017). From a nutritional point of view, 100 g of meat of the most common meat species (beef, chicken, pork, turkey, lamb, rabbit, duck) provide 20 g of high biological value protein and 8 g of fat, with an average 160 kcal/100 g product, as well as significant amounts of essential fatty acids (EFA), B-vitamins and minerals, including key trace elements. Specifically focusing on protein, meat contains all the essential amino acids (EAA) including the branched chain amino acids, which are pivotal for protein synthesis (Pereira and Vicente, 2022). Fat content and fatty acid (FA) profile are linked to the animal species and considered meat cut, as well as on the feeding and breeding strategies. However, meat can be considered a source of EFA (i.e., arachidonic acid) and, more in general, of fatty acids with beneficial effects on human health such as oleic acid, and polyunsaturated FA (PUFA) of the omega-3 series (De Smet and Vossen, 2016). Among B-vitamins, for which meat provides a relevant contribution to meet daily recommended intakes, a special focus needs to be pointed on the vitamin B_{12}. It is present almost solely in animal-origin food and its deficiency, which leads to megaloblastic anemia and a high level of blood homocysteine (cardiovascular disease risk factor that can determine depressive symptoms and neurologic impairment), is a concrete health risk factor (Green and Miller, 2005). Among meat minerals, it is worth to mention zinc (key factor for the immune system, reproductive function, cell division, growth, and several enzymatic processes), selenium (crucial for antioxidant defenses), and iron in the heme form (high bioavailability and easy absorption). Animal-tissue foods are the sole source of this essential mineral whose dietary supply is crucial to compensate for endogenous iron losses. This is pivotal for a balanced and healthy diet, to prevent health issues (Archundia-Herrera et al., 2024). A last point to be stressed before discussing meat alternatives is that meat, in order to guarantee its nutritive role for human health, needs to be correctly cooked. In fact, existing research highlights that the choice of the cooking method (i.e., boiling, stewing, grilling barbecuing, frying, etc.) and temperature, besides improving food safety, can improve or worsen the digestibility of some nutrients (i.e., protein) as well as prevent or promote the formation of compounds harmful to human health (i.e., heterocyclic aromatic amines and polycyclic aromatic hydrocarbons) (Kaur et al., 2014; Oberli et al., 2016; Suleman et al., 2020).

Plant-based Meat Alternatives

Plant-derived proteins represent so far the most exploited raw material in the manufacturing of meat alternatives. Particularly soybean proteins have been the main ingredient of most alternatives, including tofu and tempeh (Vallikkadan et al., 2023). In the 1960s, these alternatives pioneered the production of textured vegetable proteins (TVP): protein extrudate possessing tailored, stable meat-like textural properties, discovered by combining various plant-based proteins with other ingredients. TVP have been essential to create the first plant-based meat analogs (PBMA) (Vallikkadan et al., 2023), whose market achieved the peak in sales and new products launches from 2019 to 2021 (Andreani et al., 2023), with the EU holding the largest market share (Boukid, 2021). Despite the rapid market growth, products that perfectly resemble meat at the nutritional, sensory, and microstructural level have not been produced yet (Xiong, 2023). Conversely, commercially available products are characterized by an important nutritional variability, often presenting contrasting results (Cutroneo et al., 2022; Bogueva and McClements, 2023; Flint et al., 2023). Analytical studies conducted in various markets in the US (Harnack et al., 2021; Swing et al., 2021) and EU (Alessandrini et al., 2021; Petersen and Hirsch, 2023) have found that, compared to meat, PBMA generally present higher contents of salt, energy, and total carbohydrates, including both fibers and sugars. Concerning fats, PBMA generally have lower contents of both total and saturated fats compared to red meat yet higher compared to white meat (Petersen and Hirsch, 2023). Cholesterol is typically not detected as expected (Swing et al., 2021), since its presence would be linked with the present of animal material or microbial fermented plant proteins. The total protein content is lower when compared to meat (Alessandrini et al., 2021; Harnack et al., 2021; Petersen and Hirsch, 2023). Furthermore, it is noteworthy considering that plant proteins have a lower quality than animal proteins, mainly due to an unbalanced EAA profile. The combination of legumes and cereals could solve this problem, albeit their integration could raise the caloric content of the product, thus leading to excessive caloric intake (van der Heijden et al., 2023). The lower protein quality is also related to reduced digestibility, hampered by the presence of antinutritional factors and the industrial processing that PBMA undergo (Harnack et al., 2021). The micronutrients data for PBMA are inconsistent, with high calcium and sodium levels. Iron and zinc contents are generally also high, but their bioavailability is hampered by phytates, mineral antagonism, and fibrous compounds (Swing et al., 2021). The existing literature does not provide sufficient and clear information about this (Flint et al., 2023), which should instead be carefully investigated. Especially iron bioavailability represents a significant factor to be considered, since an appropriate intake of bioavailable iron is a key nutritional aspect for a healthy life. In fact, an inadequate ingestion of bioavailable iron leads to deficiency, which is the predominant cause of anemia (Pasricha et al., 2021). Iron deficiency was recently reported to affect more than 1.2 billion people worldwide, and it is considered a threat to health and quality of life. Recent data indicate that it is among the top five causes of years lived with disability and, when considering low- and middle-income countries, it is the top cause (Brittenham et al., 2023). B-vitamins, excluding B_3, B_5, and B_{12}, tend to be higher in PBMA, although bioavailability might be negatively affected by Maillard reactions and mineral antagonism. PBMA show increased vitamin E levels, whereas vitamins A and D are generally below the detection limit compared to animal-based products (Swing et al., 2021). Due to these differences PBMA cannot fully replicate meat's nutritional composition. Indeed, a metabolomics study by van Vliet et al. (2021) highlighted that certain nutrients, such as vitamin B_{12} and niacin, are exclusive to meat and meat products, whereas vitamin C, phytosterols, and some antioxidants are prevalent in PBMA. Despite proposals for fortification to address these nutritional gaps, these approaches prompt concerns about the nutritional sustainability of these products. Fortification with isolated nutrients typically falls short of providing the same nutritional benefits as consuming nutrients within a whole-food matrix (van Vliet et al., 2021). Hence, future research should delve into comprehensive investigations centered on raw material properties and processing technologies to bridge the existing nutritional gaps in PBMA.

The integration of PBMA in the diet and their outcomes on consumer health has been assessed in various randomized controlled trials (RCT). Vatanparast et al. (2020) and Farsi et al. (2022) found that PBMA, when integrated into the diet, increase fiber intake, thus improving the cholesterol profile. Toribio-Mateas et al. (2021) demonstrated that occasional substitution of meat with PBMA could benefit the gut microbiota due to prebiotic compounds like beta-glucans. While protein-rich foods pose a risk for hyperuricemia, Havlik et al. (2010) found that soy and wheat had lower purine contents than animal-derived foods. PBMA can therefore be promising substitutes to purine-rich foods, helping consumers to lower the occurrence of gout and kidney stones. The high protein and fiber contents of plant-based foods offer various health benefits, including increased satiety and prevention of many non-communicable diseases (NCDs) (Farsi et al., 2022). However, the positive effects may be compromised to some extent by the extensive processing of raw materials (Flint et al., 2023). Most PBMA fall into the UPF category in the NOVA classification system, due to sophisticated industrial technology required and extensive ingredients lists (Siegrist and Hartmann, 2023). In terms of technology, the majority of produced PBMA undergo extrusion, exposing them to extreme conditions of temperature, moisture, and pressure (Hadi and Brightwell, 2021).

Besides worsening TVP sensory properties, extrusion has been found to have detrimental effects on the nutritional composition of TVP. This includes the generation of thermally induced toxic compounds such as advanced glycation and lipid oxidation end products (Xiong, 2023), and various carcinogens, including many polycyclic aromatic hydrocarbons and nitrosamines (He et al., 2020). Most plants naturally contain antinutritional compounds like phytates, trypsin inhibitors, tannins, leptins, oxalates, etc., known to impede the digestibility and systemic bioavailability of proteins (van der Heijden et al., 2023) and several minerals (Bogueva and McClements, 2023). While processing methods like extrusion can minimize or deactivated these compounds, trace amounts may persist in the final product (Bogueva and McClements, 2023). The extreme processing conditions are also crucial for mitigating the rising incidence of plant-derived allergic reactions. However, the extent of their reduction and the immunological response to residual elements still require further evaluation (Hadi and Brightwell, 2021; Bogueva and McClements, 2023). After extreme physical changes, TVP undergoes additional processing for consumer palatability. This involves the incorporation of sugars, salt, various food additives (i.e., emulsifiers, flavors, colorants, etc.), and diverse micronutrients to emulate meat's nutritional profile (Andreani et al., 2023; Bogueva and McClements, 2023; Flint et al., 2023). It is noteworthy that strategies mimicking meat-like properties have a dual impact, both negatively affecting the naturalness and healthiness of raw materials as well as consumer perception. Future studies are therefore vital to unveil innovative technological solutions that can limit the industrial processing of PBMA, preserving plant-derived health benefits while reducing hazardous compounds like allergens and antinutritional factors. Additionally, clinical studies are essential to address lingering concerns about the long-term consumption of PBMA and determine their sustainability as meat alternatives.

Algae-based Meat Alternatives

Algae, classified as macro and microalgae, have emerged as a promising dietary protein source, gaining traction in many developed countries. They are increasingly seen as a nourishing and sustainable option amid the shift from animal to vegetable protein. Furthermore, their attractive array of bioactive and functional compounds enhances their potential as food ingredients. Despite these promising properties, algae-based meat alternatives are still at a developmental stage (Espinosa-Ramírez et al., 2023), impacting their nutritional sustainability at the raw material level.

Algae exhibit extreme heterogeneity in composition among species, with variations influenced by factors such as location and cultivation season (Espinosa-Ramírez et al., 2023). Microalgae protein content spans from 23% to 63% of their dry matter (DM) (Kumar et al., 2022), with widely available species such as *Arthrospira platensis* and *Chlorella vulgaris* reaching up to 70% and 60% DM, respectively (Dalle Zotte et al., 2014; Parisi et al., 2020; Gohara-Beirigo et al., 2022; Espinosa-Ramírez et al., 2023). Macroalgae generally contain lower proteins than microalgae, ranging from 3% to 47% DM (Espinosa-Ramírez et al., 2023). Despite a lower content, macroalgae exhibit higher bioavailability (Kumar et al., 2022) than microalgae, as in the latter the cell wall retains proteins to some extent (Espinosa-Ramírez et al., 2023). It is essential to note that algal protein content is often overestimated since it is based on total nitrogen content, considering non-protein nitrogen found in nucleic acids, cell wall components, and intracellular compounds (Kumar et al., 2022; Espinosa-Ramírez et al., 2023). In general, the EAA content of both macro- and microalgae is nearly comparable to reference protein-rich sources (i.e., eggs, meat). Both algae groups present a relatively complete EAA profile; many species, however, tend to be lower especially in sulfur-containing amino acids, including cysteine and methionine (Wan et al., 2019; Kumar et al., 2022). To date, digestibility data of algae-derived proteins are limited at Protein Digestibility-Corrected Amino Acid Score (PDCAAS) assessed through animal bioassay or *in vitro* studies, with no human digestibility trials having being conducted yet. The PDCAAS for both macroalgae and microalgae are lower compared to reference proteins like those of eggs, soybean, and any animal-derived protein sources (Parisi et al., 2020; Kumar et al., 2022; van der Heijden et al., 2023). However, mechanical processing technologies show promise in enhancing microalgae digestibility and, consequently, nutrient bioavailability (Kumar et al., 2022; Espinosa-Ramírez et al., 2023). In terms of carbohydrates, macroalgae generally have higher contents compared to microalgae, along with a distinct polysaccharide profile. Most macroalgae contain hydrocolloids, largely extracted for industrial purposes due to their gelling and emulsifying properties (Wan et al., 2019). On the other hand, microalgae primarily contain cell wall-related polysaccharides, serving as dietary fiber (Gohara-Beirigo et al., 2022). Algae boast an appealing fatty acid profile, predominantly composed of ω-3 PUFA, specifically eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in microalgae (Gohara-Beirigo et al., 2022) and EPA and α-linolenic acid in macroalgae (Wan et al., 2019). However, the low percentage of lipids in algae suggests the need for substantial supplement or fortified food consumption to achieve notable health benefits (Gohara-Beirigo et al., 2022). Turning to micronutrients, both macro and microalgae serve as significant sources of many key micronutrients, such as phosphorous, potassium, sodium, zinc, iron, calcium, and magnesium, owing to their ability to bioaccumulate elements from the environment (Wan et al., 2019; Gohara-Beirigo et al., 2022; Espinosa-Ramírez et al., 2023). One key aspect to be pointed out regarding the nutritional properties of algae is that their intrinsic composition (thickness and rigidity) is known to affect their digestibility and nutrient absorption by the human organism. In this sense, appropriate processing techniques (bead milling, high pressure homogenization with enzymatic pretreatment, using cellulases prior to algal compound extraction) appear to be fundamental to increase the extractability and bioavailability of algae nutrients, including protein and amino acids, lipid and fatty acids, pigments and minerals (Demarco et al., 2022).

As for vitamins, algae are primarily rich in antioxidant vitamins such as vitamins E and C. Additionally, they contribute to some B-complex vitamins, including vitamin B_2, B_3, and B_{12} (Wan et al., 2019; Parisi et al., 2020; Gohara-Beirigo et al., 2022). However, further investigations into algal B_{12} content are needed, given the potential of overestimation (van den Oever and Mayer, 2022). Key components of algae are pigments, notably carotenoids, phycocyanin and chlorophyll, all linked to important antioxidants and other bioactive activities (Wan et al., 2019; Gohara-Beirigo et al., 2022). These beneficial features are complemented by a diverse array of bioactive peptides (BAP) serving as mediators with antioxidant, antihypertensive, anti-inflammatory, antimicrobial, and anticarcinogenic properties (Espinosa-Ramírez et al., 2023). While the development of supplements or functional foods using algal BAP holds great promise, several challenges persist. Consistent efforts need to be addressed to the scant research and industrial technologies in order to better isolate and comprehend the therapeutic properties of these BAP (Kumar et al., 2022; Espinosa-Ramírez et al., 2023). Cultivating algae offers an intriguing aspect, allowing the customization of nutritional composition by simply adjusting growth environmental conditions (Wan et al., 2019; Kumar et al., 2022; Espinosa-Ramírez et al., 2023). Under adverse conditions, algae employ defense mechanisms by accumulating specific metabolites. For instance, reducing nitrogen (Guccione et al., 2014) or phosphorus (Markou et al., 2012) levels in the medium leads to decreased protein and photosynthetic pigment synthesis, accompanied by the simultaneous accumulation of carbohydrates and lipids. This adaptable nutritional profile, coupled with its plasticity during cultivation, positions algae as a valuable tool for industrial food formulation. This versatility is demonstrated by various staple foods in the market, encompassing meat products (Espinosa-Ramírez et al., 2023) and meat alternatives (Bryant, 2022).

Despite the numerous advantages, the food industry encounters challenges in incorporating algal biomass into staple foods, with poor palatability and appearance as major barriers (Espinosa-Ramírez et al., 2023). Excessive algae inclusion, whether in plant-based (50%) (Grahl et al., 2018) or animal-based products (40%) (Cox and Abu-Ghannam, 2013) has led to diminished sensory acceptance, imparting a fishy aroma and intense green color to the final product. Kumar et al. (2022) advise limiting algal incorporation to no more than 10% of the total formulation to avoid adverse alteration in taste, appearance, and texture, suggesting an optimal inclusion level between 3% and 4%.

Regular consumption of algae-based foods raises concerns about potential health effects due to nucleic acids, heavy metals, and toxin presence. Microalgae genera with high multiplication rates, like *Arthrospira* sp. and *Chlorella* sp., contain elevated nucleic acids levels, necessitating thermal pre-treatment to prevent hyperuricemic conditions and related issues (Kumar et al., 2022). As previously noted, algae have the ability to bioaccumulate various compounds from their surroundings, hence traces of heavy metals may be present in the final products, particularly in algae cultivated in polluted environments (Kumar et al., 2022; Espinosa-Ramírez et al., 2023). Additionally, algal toxin occurrence is linked to absorption processes or the cultivation of toxin-producing strains, prevalent in microalgae groups such as dinoflagellates and cyanobacteria (the latter includes *A. platensis*) (Kumar et al., 2022).

While algae's nutritional and functional benefits offer a promising alternative to synthetic additives, concerns about their sustainability persist due to limited knowledge and innovation. Algae cultivation and processing are in early developmental stage, hindering efficient scaling-up and the creation of algae-based meat alternatives. Furthermore, the nutritional sustainability of algae necessitates further clinical studies, especially regarding the long-term consumption of algae-based products.

Fungi-based Meat Alternatives

Fungi are notably available in the global market, presenting a high culinary importance in many countries worldwide. Among them, only *Fusarium venenatum* has been widely exploited to successfully create a fungi-based meat analog, branded as Quorn™ (Xiong, 2023). Besides *F. venenatum*, other fungal species such as *Neurospora intermedia*, *Pleurotus albidus,* and *Aspergillus oryzae* have been used in mycoprotein production (Khan et al., 2023). Mycoprotein is considered a sustainable protein-rich biomass produced through the agro-industrial wastes fermentation from vegetative mycelia inside specific bioreactors. Mycoprotein is a promising building block in the production of fungi-based meat alternatives, presenting useful functional properties, particularly rheological and textural properties (Khan et al., 2023), as well as an attractive flavor, preferred by consumers when compared to other plant-based alternatives (Elzerman et al., 2011). Nutritionally, mycoprotein is acknowledged as a wholesome food, providing high-quality proteins and dietary fibers, coupled with low levels of fats and energy (Hashempour-Baltork et al., 2020). In terms of protein content, mycoprotein demonstrates an average comparable to eggs but falls below levels found in soy and meat (Khan et al., 2023). Despite this, its EAA profile is considered balanced according to WHO/FAO recommendations for all EAA (van der Heijden et al., 2023). Furthermore, fermented fungal proteins exhibit notable digestibility (PDCAAS of 1.00), placing their protein absorption rates on par with those of cooked egg whites, poultry meat, and casein (Khan et al., 2023).

Mycoprotein fat content is relatively low (Hashempour-Baltork et al., 2020; Khan et al., 2023), featuring an intriguing FA profile primarily composed of PUFA (van der Heijden et al., 2023). Another distinctive feature of mycoproteins is their designation as a "high fiber" food by the European Commission (Derbyshire and Delange, 2021) due to the elevated content of β-glucans and chitin, important cell walls insoluble polysaccharides, known to enhance gut microflora and confer various health benefits (Hashempour-Baltork et al., 2020; Derbyshire and Delange, 2021; Khan et al., 2023).

From existing data, it appears that mycoproteins have adequate zinc and selenium contents as well as interesting B-complex vitamin amounts, but they are low in sodium, iron, and vitamin B_{12}. Furthermore, robust bioavailability studies on the aforementioned compounds seem not to be available yet (Hashempour-Baltork et al., 2020; Khan et al., 2023), which is a scientific gap that surely needs to be addressed. Similar to algae, mycoproteins contain various pigments, including flavins, quinones, and melanin, contributing to their appealing properties. Furthermore, certain fungi contain thiols, important for their high antioxidant activity (Derbyshire and Delange, 2021).

Diverse effects of mycoprotein consumption on human health have been already assessed through randomized clinical trials focusing on specific outcomes (Derbyshire and Delange, 2021). Mycoprotein consumption demonstrates remarkable satiating effects, surpassing those of an isocaloric chicken-based meal, with lower energy intake attributed to increased short-chain fatty acids FA (SCFA) production, prolonging satiety (Harris et al., 2019). These fiber-derived

SCFA offer various benefits, from maintaining a healthy gut environment (Hashempour-Baltork et al., 2020) to apparently improving overall cholesterol profile (Coelho et al., 2021). However, the regulation of glycemic and insulin responses to mycoprotein fiber has yielded inconsistent results in different consumption trials. A recent study by Coelho et al. (2021) found no significant variations in blood glucose and insulin levels between mycoprotein-based and a chicken-based meal, suggesting these beneficial effects might be more prominent in consumers with overweight and obesity. The current literature also underscores mycoprotein potential to supply an array of antioxidant compounds originating from biomass fermentation or microbiota-driven catabolic reactions (Khan et al., 2023).

Despite being considered a safe food ingredient, mycoproteins have been also associated to different adverse health reactions. Common symptoms associated with mycoprotein consumption include itching, nausea, vomiting and diarrhea, particularly pronounced in individuals with mold allergies (Khan et al., 2023). Despite the presence of allergens in mycoproteins allergic responses are relatively uncommon, as evidenced by a large clinical trial conducted by Jacobson and DePorter (2018) in the UK. Implementing an appropriate labelling program and ensuring consumers possess adequate preparation and cooking knowledge can help minimize the occurrence of fungi-related allergic reactions. Concerning mycotoxins, the commercially used *F. venenatum* A3/5 strain is deemed non-pathogenic (Hadi and Hardwell, 2021). However, genes encoding for different mycotoxins have been found in its genome, necessitating precautionary analysis before final product commercialization. Mycotoxin occurrence may also be linked to the agro-industrial biomass used for mycelia growth, potentially introducing pollutants such as heavy metals (Hadi and Hardwell, 2021). The fast growth rates of fungal cells in bioreactors have showed to increase nucleic acid contents, potentially resulting in hyperuricemic condition when mycoproteins are frequently consumed. Fortunately, specific thermal treatments during mycoprotein production can effectively reduce purine levels below safety thresholds (Khan et al., 2023).

Overall, the current literature positions mycoproteins as a promising food ingredient and a valuable alternative to both animal- and plant-derived proteins. Its introduction into conventional diets is generally seen as beneficial for consumer health, particularly for individuals with overweight and obesity. However, these promising effects still require in-depth knowledge, as some findings, such as glucose and insulin levels, remain inconsistent (Derbyshire and Delange, 2021). Hence, mycoproteins could be a valuable ingredient in formulating meat alternatives or hybrid products. However, it is noteworthy to consider that the degree of processing necessary to achieve the desired meat-like characteristics may impact the overall sustainability of this whole food.

Insect-based Meat Alternatives

Insects are emerging as a novel food with increasing significance in the food industry of Western countries, due to their considerable nutritional value and production efficiency, though their development faces ongoing challenges related to negative consumer perceptions (Baiano, 2020). To counteract this, many food industries have opted to process and incorporate insects into staple foods, aiming to reduce common insect-related food neophobia. However, these fortified foods introduce a novelty for the food industry, requiring updated knowledge on the technological and sensory effects resulting from insect incorporation, as well as their long-term impact on human health (Borges et al., 2022). The limited knowledge in this area currently hinders the development of meat alternatives based solely on insects.

Insects exhibit a highly diverse nutritional composition influenced by internal factors, such as species and metamorphosis stages (larvae, pupae, and adult), as well as external factors like location, feed, rearing, and measuring methods (Borges et al., 2022; Tassoni et al., 2022). Proteins, constituting a significant portion of macronutrients, range widely from 25% to 75% of DM, although crude protein content is often overestimated due to high non-protein nitrogen level (Oonincx and Finke, 2021). The amino acid profile is generally considered balanced across orders, meeting WHO/FAO recommendations for all EAA, with deficiencies identified in the *Blattodea*, *Hemiptera*, and *Isoptera* orders (van der Heijden et al., 2023). Protein digestibility data remain limited to *in vitro* and animal studies, with human Digestible Indispensable Amino Acid Score (DIAAS) yet to be documented and PDCAAS ratings established only for some beetles, silkworms, and mealworms. Despite lower digestibility than animal-derived proteins, insect PDCAAS remain higher than vegetal proteins (van der Heijden et al., 2023). The exoskeletal chitin in insects, however, contributes to decreased digestibility by binding amino acids to varying extents (Oonincx and Finke, 2021). The typical high protein contents make insects an important source of BAP with various activities, including antioxidant, anti-inflammatory, antimicrobial, antifungal, antitumoral, and cardio-protective effects (Acosta-Estrada et al., 2021).

The lipid content varies between 10% and 70% of DM, with the highest levels typically observed in industrially cultivated insects and nymphs. Lipid profile and cholesterol levels vary by species, developmental stage, and diet (Oonincx and Finke, 2021). The lipid fraction may contain variable amounts of bioactive compounds, mainly EFA, phospholipids, sterols and waxes, with favorable effects on human health (Acosta-Estrada et al., 2021). Insects also contribute to dietary fibers, primarily in the form of chitin, an essential component of their exoskeleton, with content increasing with the insect life-stage (Oonincx and Finke, 2021). When partially digested, chitin and its metabolites demonstrate important biological activities, including immune-boosting properties, as well as antioxidant, antifungal and antitumoral effects (Acosta-Estrada et al., 2021). Similar to meat, insects provide limited quantities of carbohydrates, mainly remnant of food found in their gastrointestinal tract (Oonincx and Finke, 2021).

The micronutrient profile of insects varies greatly among orders and is profoundly affected by external factors such as diet. Generally, insects are considered rich sources of both macro- and micro-minerals, encompassing phosphorous, magnesium, potassium, sodium, iron, zinc, manganese, copper, and selenium. Conversely, calcium content tends to be low due to the absence of a mineralized exoskeleton. While overall mineral bioavailability is high, it can be hampered by various antinutrients, including phytates, tannins, and oxalates, which accumulate in the gastrointestinal tract from ingested plants (Oonincx and Finke, 2021). Regarding vitamins, insects exhibit an intriguing profile, serving as significant source of vitamin A (in highly available retinoid form), D, E, and all B-complex vitamins except thiamine. However, the vitamin profile of insects is markedly influenced by their diet and industrial processing, with wild insects generally containing higher concentrations of all vitamins, particularly A and E, compared to most cultivated insects (Oonincx and Finke, 2021). In general, the nutritional composition of insects positions them as a nourishing and healthy source of nutrients, suitable for consumption as whole food or as an ingredient to enhance the nutritional profile of various familiar foods (Acosta-Estrada et al., 2021).

Despite their benefits, regular intake of insect-based foods may induce gout and kidney stones due to the prevalent high purine levels in many species, similarly to commonly consumed animal products (Acosta-Estrada et al., 2021). Additionally, insects may also contain hazardous substances, primarily in the form of allergens and environmental pollutants, including pesticides, mycotoxins, and heavy metals. The presence of allergen compounds raises concerns about the safety of insect-based foods. Documented allergenic reactions are often triggered by proteins like tropomyosin and arginine kinase, commonly found in arthropods such as crustaceans and dust mites, recognized as allergens by our immune system. Implementing proper food labelling through appropriate legislation stands as the optimal solution to mitigate the occurrence of allergic reactions (Hadi and Brightwell, 2021).

Concerning contaminants, certain heavy metals, including arsenic, lead, cadmium, and mercury, have been reported to bioaccumulate in insects, impairing growth rates and mineral profiles (Oonincx and Finke, 2021). Furthermore, documentation on mycotoxin and pesticide bioaccumulation in edible insects is still limited. Gützkow et al. (2021) have showed that mycotoxins did not accumulate when added to the diet of mealworm (*Tenebrio molitor*) larvae, being instead excreted or degraded. The effects of their metabolites, however, still require further assessments. As established by the European Food Safety Authority (EFSA), insects raised in controlled environments and with feed produced following Good Manufacturing Practice (GMP) represent a scarce source of environmental contaminants. According to the clinical studies concerning the safety of the authorized species in the EU market, all groups of contaminants encompassed in the trial (i.e., heavy metals, mycotoxins, and pesticides) did not reach the maxim levels set for other novel foods, with some of them below the detection levels. These novel foods can therefore be deemed safe and unlikely sources of these hazardous chemicals (EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA) et al., 2021a, 2021b, 2021c).

Apart from allergens and contaminants, microbial hazard is a critical step concerning the entire insect production chain. Fresh insects, regardless of the species, often exhibit elevated microbial contamination, frequently surpassing the limits set by food safety authorities (Acosta-Estrada et al., 2021). However, maintaining suitable environmental conditions from rearing to shipping can profoundly impact microbial proliferation. Consequentially, processing steps such as drying, acidification, or thermal treatments (e.g., blanching or sterilization) must be applied to control the growth of both spoilage and pathogen microbes. These processes, combined with appropriate hygiene practices, can ensure the safety of the final product while simultaneously enhancing its shelf-life (Acosta-Estrada et al., 2021; Hadi and Brightwell, 2021). The same claims were established also by the EFSA for the EU marketable species, which did not exceed hazardous thresholds even after a 12-month period. Furthermore, no pathogens appertaining to *Listeria* spp. and *Salmonella* spp. genera were found in the final product (EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA) et al., 2021a, 2021b, 2021c).

Despite the mentioned challenges, the potential of using insects as both whole food and ingredients in staple foods like bakery and meat products is driving research to bridge scientific and sustainability gaps (Borges et al., 2022). These gaps, along with the negative consumer perceptions, currently impede the broader adoption of insects as an alternative protein source. However, with the continuous advancements in insect farming and processing, the potential to expand the use of insects as a viable alternative protein source in hybrid products is growing.

Cultured Animal Cells

Before delving into this category of food products, it is important to emphasize that the term "cultured animal cells" has been chosen in accordance with international guidelines, based on the matter of fact that it is improper to refer to such product as meat. Indeed, by recalling the definition of meat (see the section "The nutritional role of meat") there emerges a structural complexity that cannot currently be mimicked by available industrial tools. In the field of lab cultivation of muscle fibers and associated muscle structures, substantial scientific and technological advancements have occurred within a short span of decades, driven by the goal of mimicking traditional meat. Since the inception of the inaugural patent in 1999, a multitude of start-ups have surfaced worldwide, all dedicated to the pursuit of replicating an equivalent of animal muscle (Broucke et al., 2023). The general manufacturing process of cell-based food can be divided into four stages: 1) cell selection, tissue biopsy, and isolation; 2) cell growth and differentiation; 3) cell harvest; and 4) processing and formulation of the harvested biomass (FAO and WHO, 2023). Despite the fervent claims of various food companies, several aspects remain shrouded in uncertainty. Critical considerations such as food safety, sensory characteristics, purchase costs, scale-up technologies, and legislative frameworks demand examination before the seamless integration of these alternatives into the market. It is essential to note that a substantial proportion of these products is currently proved unmarketable, primarily due to their failure to replicate the traditional quality traits associated with conventional meat (Broucke et al., 2023). Furthermore, very few countries have established definitive legislation pertaining to both the production and sale of cell-based food. The first one was Singapore with cultured chicken nuggets (FAO and WHO, 2023), followed by the US, where the Food and Drug Administration (FDA) allowed the sale of cultured chicken (*Gallus gallus*) cells (FDA, 2023), and then Israel, where the Ministry of Health approved, in 2024, cultivated beef cells (https://www.gov.il/en/departments/news/17012024-02). Specifically focusing on the US, the two regulatory agencies responsible for the safety of cell-based food (FDA and the US Department of Agriculture's Food Safety Inspection Service [FSIS]) recently acted to facilitate the possibility for the industry to bring cell-based food to US consumers. Nonetheless, regulations regarding the labelling of cell-based food have not been finalized yet; therefore, any prior approved labels may have to change according to settled regulations. Together with granting specific company approvals, in June 2023 the FSIS proclaimed two directives to guide food safety inspection of cell-based food and to update sampling procedures (Pugliese and Crotty, 2024). On the front of safety, however, comprehensive studies on long-term effects on human health remain notably absent, rendering the nutritional sustainability of cell-based food reliant on assumptions.

The nutritional profile of cell-based food is still unclear, hindered by the absence of testable products and a lack of transparency in existing production chains (Olenic and Thorrez, 2023). Although the extent of the nutritional gap is still unknown, it is evident that cell-based food differs from conventional meat. The collected and isolated animal cells exhibit a distinct nutritional composition compared to the tissue intended to be replicated (Olenic and Thorrez, 2023). As a result, various processing methods, such as cell genetic modification or fortification, become imperative to achieve the desired nutritional composition (Broucke et al., 2023), though the repercussions on the final product's sustainability remain uncertain (Wood et al., 2023).

At the nutrient level, both the quantity and quality of protein in cell-based food have not been adequately assessed or quantified (Broucke et al., 2023). Notably, recent findings by Joo et al. (2022) underscored significant differences in the amino acid profile (and consequently, taste) between satellite cells taken from bovines and chickens compared to conventional meat. Consequently, the food industry must grapple with the challenge of adjusting the amino acid composition of satellite cells, recognizing that simply supplementing missing amino acids in the cultivation medium does not guarantee their absorption by the satellite cells (Joo et al., 2022). The amino acid composition of cell-based food can also be influenced by the scaffold: a 3D structure made of various materials (organic or synthetic) that aids in the growth and differentiation of cells, ensuring a proper flow of oxygen and nutrients throughout the biomass. It is noteworthy that most organic scaffolds are protein-based, potentially altering the amino acid composition of the final products. The intricate interplay between these variables underscores the complexity of achieving nutritional consistency and quality in cell-based food.

Animal proteins (i.e., collagen or fibrin) could serve as scaffold materials, although they might adversely affect the EAA profile of the final product. Alternative edible scaffold materials, such as plant- or algae-derived TVP or polysaccharides, are gaining significance (Seah et al., 2022; Broucke et al., 2023). However, the use of dietary fiber would alter the composition of the cell-based food fibers, resulting in products that deviate from the characteristics of conventional meat (Seah et al., 2022).

Meat presents a complex lipid profile that cannot be faithfully replicated solely through the cultivation of adipose stem cells. To address this, the addition and regulation of fats directly in the cultivation media emerge as a potential solution to cover deficiencies. However, it is crucial to note that the straightforward addition of fats to the media may have adverse effects on cellular growth (Fraeye et al., 2020; Broucke et al., 2023). Throughout cell proliferation, all micronutrients essential for the cellular growth are supplied with the cultivation medium. Nevertheless, the uptake and accumulation mechanisms of *in vitro* growing cells remain unclear. Some minerals and vitamins, such as vitamin B_{12}, require specific binding and transport proteins for cellular entry. Additionally, micronutrient supplementation may have different effects on human health compared to nutrients provided by whole-foods matrices like conventional meat. Consequently, in-depth investigation is imperative to determine whether the simple addition of nutrients to the media represents a cost-effective and health-sustainable strategy (Broucke et al., 2023; Wood et al., 2023).

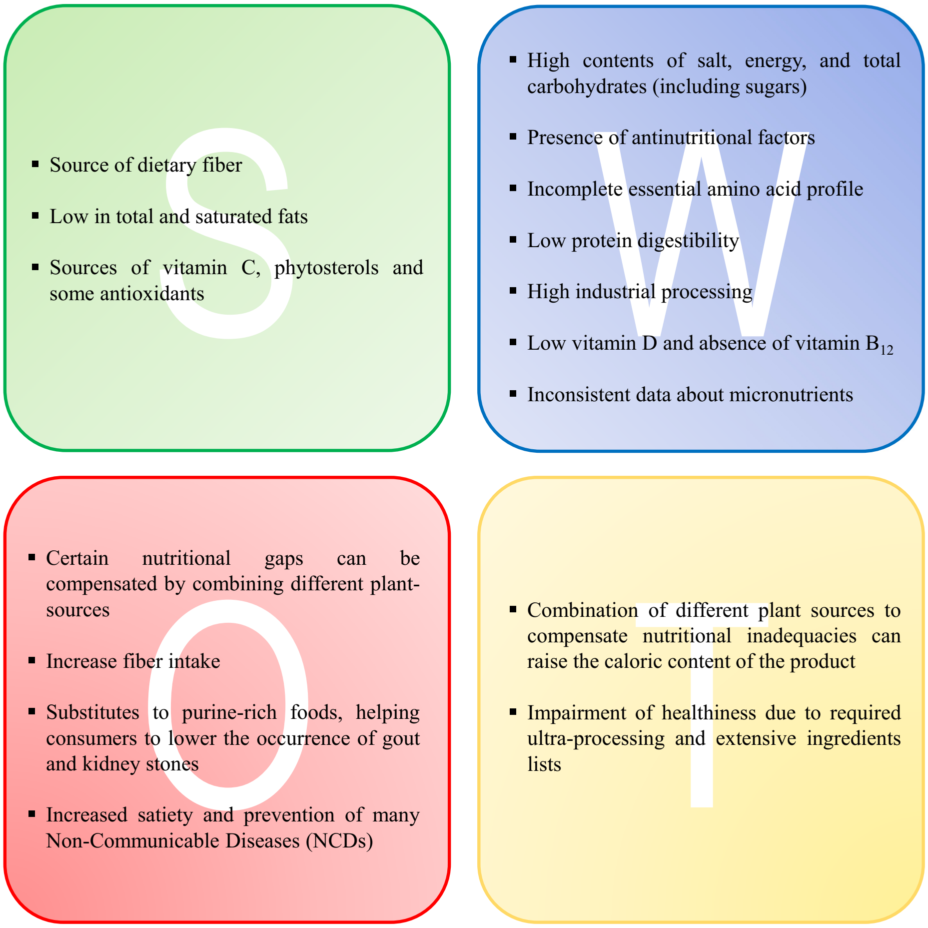
The cell-based food also lacks several bioactive compounds, such as creatine and taurine, which are essential sources in conventional meat (Fraeye et al., 2020). Therefore, despite the impressive innovation received, cell-based food still significantly differs from conventional meat at a nutritional level. This also applies to other techno-functional and sensory properties that have not yet been achieved but are crucial in consumer acceptance. The challenges related to the replication of each meat properties have been thoroughly assessed in the review by Broucke et al. (2023).

Cell-based food is produced in highly controlled environments, instilling a sense of safety against food-related hazards. However, the FAO and WHO (2023) have identified up to 53 potential health hazards along the entire production chain, with the most significant and recurring ones assessed below. Many of these hazards are known and can be commonly found in conventionally produced food products, whereas others are specifically related to *in vitro* cell growth. Microbial contamination represents the primary hazard for these products and can be encountered throughout the production chain, from animal biopsy to biomass packaging. Besides representing a hazard to humans, microbial proliferation is also detrimental to proper animal cell growth and differentiation. Common prophylaxis measures include following good hygiene practices (GHP), regular monitoring, and antibiotics, for which residues could potentially generate drug-resistant strains and other detrimental effects (Broucke et al., 2023; FAO and WHO, 2023). After tissue cell isolation, the addition of a cultivation media might introduce various microbes and allergens, along with harmful contaminants such as microplastics, heavy metals, and chemical compounds (FAO and WHO, 2023). During cellular differentiation, the biomass must be carefully separated by media and scaffold (if not edible or biodegradable). Inadequate harvesting could lead to the occurrence of bioactive compounds such as hormones and growth factors in the edible biomass, some of which are associated to metabolic alterations and cancer development when frequently consumed. Furthermore, chemical cell-separation techniques for scaffold removal and residues thereof could represent additional hazards to consumer health (Broucke et al., 2023; FAO and WHO, 2023). Lastly, during biomass processing, various food additives are added, increasing the risk of allergenic and digestive problems (FAO and WHO, 2023). The packaging of these products should be regulated by strict legislation, essential for adequately warning consumers and minimizing the risk of adverse health effects. Accordingly, labels should include all ingredients and mention potential allergens (FAO and WHO, 2023).

Cell-based food aspires to emerge as a promising alternative to conventional meat, promoting sustainability and ethical practices. Despite start-ups claiming the imminent disruption of the traditional meat market with their products, convincing evidence remains elusive (Siegrist and Hartmann, 2023; Wood et al., 2023). Addressing critical issues is imperative, given the current lack of fundamental knowledge, rendering the market application of these products unfeasible. Beyond considerations of productivity and legislation, comprehensive investigations are required to evaluate whether cell-based food can truly serve as sustainable and nourishing sources of nutrients comparable to traditional meat. The path of cell-based food is at a crucial juncture, demanding careful consideration and ongoing research to ensure both safety and sustainability in the evolving landscape of alternative protein sources.

Swot Analysis on Nutritional Sustainability of Meat Alternatives

After evaluating the benefits and hazards associated with each meat alternative product, much remains to be inferred to ascertain whether these novel food products really represent a sustainable replacement for their animal counterparts and provide a viable solution to face the ongoing challenges of increasing protein demand and climate changes. When mentioning the term sustainability, the present article refers to a sustainable food system (FAO, 2018), i.e., “a food system that delivers food security and nutrition for all in such a way that the economic, social, and environmental bases to generate food security and nutrition for future generations are not compromised”. Numerous barriers currently impede the integration of meat alternatives into the diets of most consumers. Optimistic projections from supporters of meat alternatives suggest that these products will reduce meat market shares rather than entirely replace them, with an anticipated coverage of 60% of the global meat market by meat



- Source of dietary fiber
- Low in total and saturated fats
- Sources of vitamin C, phytosterols and some antioxidants

- High contents of salt, energy, and total carbohydrates (including sugars)
- Presence of antinutritional factors
- Incomplete essential amino acid profile
- Low protein digestibility
- High industrial processing
- Low vitamin D and absence of vitamin B_{12}
- Inconsistent data about micronutrients

- Certain nutritional gaps can be compensated by combining different plant-sources
- Increase fiber intake
- Substitutes to purine-rich foods, helping consumers to lower the occurrence of gout and kidney stones
- Increased satiety and prevention of many Non-Communicable Diseases (NCDs)

- Combination of different plant sources to compensate nutritional inadequacies can raise the caloric content of the product
- Impairment of healthiness due to required ultra-processing and extensive ingredients lists

Figure 1. SWOT analysis related to the nutritional sustainability of the assessed plant-based meat alternatives.

alternatives in 2040 (Gerhardt et al., 2020). However, contrasting predictions have been made, considering crucial issues that still hinder the widespread adoption of these products. These issues encompass the need to replicate the nutritional and sensory attributes of meat, as well as the high retail price (Siegrist and Hartmann, 2023). The SWOT analyses of meat alternatives (Figures 1–5) summarize the key points discussed in the previous sections, categorizing them into Strengths, Weaknesses, Opportunities, and Threats related to the nutritional sustainability of these meat alternatives.

The assessed meat alternatives and raw materials emerge as promising nutrient sources, typically characterized by high protein contents, low levels of high-quality fats, and a favorable micronutrient profile. Excluding cell-based food, other meat alternatives present appealing levels of dietary fibers (Wan et al., 2019; Hashempour-Baltork et al., 2020; Alessandrini et al., 2021; Harnack et al., 2021; Oonicx and Finge, 2021; Swing et al., 2021; Gohara-Beirigo et al., 2022; Petersen and, Hirsch 2023) and various bioactive compounds, providing a wide array of health-promoting properties (Acosta-Estrada et al., 2021; Espinosa-Ramírez et al., 2023; Khan et al., 2023). Interestingly, this nutritional composition can be further enhanced by manipulating different cultivation conditions (Borges et al., 2022; Kumar et al., 2022; Broucke et al., 2023; Espinosa-Ramírez et al., 2023).

Despite inconsistencies in the literature, short-term consumption of these meat alternatives has been associated with promising health benefits, such as improvement in both cholesterol profile and gut microbiota, as evidenced by various randomized trials (Vatanparast et al., 2020; Coelho et al., 2021; Toribio-Mateas et al., 2021). With adequate knowledge and technological innovation, certain meat alternatives have the potential to provide nutritional and sensory properties equivalent to conventional meat. Consequently, they might be a solution to face the increasing meat demand, simultaneously reducing its significant overconsumption rates in many developed countries and the related adverse effects (Bryant, 2022; Siegrist and Hartmann, 2023; Smetana et al., 2023). Furthermore, meat alternatives may serve as a valuable solution to combat NCD such

- Presence of bioactive and functional compounds
- Relatively complete essential amino acid profile
- Appealing fatty acid profile, predominantly composed of ω-3 PUFAs
- Microalgae can be source of dietary fiber

- They are still at a developmental stage
- Extreme heterogeneity in composition
- Protein content is often overestimated and low digestibility data available
- Many algal species are low in sulfur amino acids
- Poor palatability and appearance
- Lower Protein Digestibility-Corrected Amino Acid Score compared to reference proteins

- Cultivation and processing are in early developmental stage
- Mechanical processing technologies can enhance digestibility and nutrients bioavailability
- Customization of nutritional composition by simply adjusting growth environmental conditions

- Low lipids content: substantial supplement to achieve notable health benefits
- Appropriate processing techniques seem fundamental to increase nutrients bioavailability
- Bioaccumulation of various compounds with potential negative health effects (nucleic acids, heavy metals, and toxins)

Figure 2. SWOT analysis related to the nutritional sustainability of the assessed algae-based meat alternatives.

- Sustainable protein-rich biomass
- High-quality proteins (essential amino acids), low levels of fats and energy
- High fiber: elevated content of β-glucans and chitin
- Adequate zinc and selenium contents
- Antioxidant properties of some species

- Low in sodium, iron and vitamin B_{12}
- Robust nutrients' bioavailability studies seem not to be available yet
- The regulation of glycemic and insulin responses to mycoprotein fiber has yielded inconsistent results in different consumption trials
- Processing necessary to achieve the desired meat-like characteristics may impact the overall sustainability

- Different species can be used in mycoprotein production
- Mycoprotein has an attractive flavor and useful functional properties (rheological and textural)
- Mycoprotein consumption demonstrates remarkable satiating effect

- Consumption associated to adverse health reactions: itching, nausea, vomiting and diarrhea
- Presence of genes encoding for different mycotoxins + possible mycotoxins accumulation from agro-industrial biomass used for mycelia growth
- Possible hyperuricemia when mycoproteins are frequently consumed: thermal treatments required

Figure 3. SWOT analysis related to the nutritional sustainability of the assessed fungi-based meat alternatives.

as obesity and cardiovascular problems (Vatanparast et al., 2020; Coelho et al., 2021; Toribio-Mateas et al., 2021; Farsi et al., 2022; Khan et al., 2023).

However, numerous weaknesses and threats identified in the SWOT analysis significantly impede the development and widespread adoption of these meat alternatives. Despite considerable efforts, meat alternatives do not currently possess the same nutritional and sensory properties as conventional meat (van Vliet et al., 2021; Olenic and Thorrez, 2023). Thus far, similar properties can only be obtained through intensive industrial processing involving extreme physical conditions and the addition of several nutrients and additives (Hadi and Brightwell, 2021; Andreani et al., 2023; Broucke et al., 2023). Apart from ultra-processing, several other drawbacks need consideration when these products are consumed frequently.

As previously indicated in this article, the raw materials under consideration consistently exhibit inferior protein quality compared to conventional meat. This is manifested by an incomplete EAA profile and/or reduced protein digestibility, influenced by various antinutritional factors (Wan et al., 2019; Oonicx and Finge, 2021; Kumar et al., 2022; Khan et al., 2023; van der Heijden et al., 2023). The substitution of meat with its alternatives may lead to nutritional deficiencies, particularly concerning vitamin B_{12} and key minerals for human health and development such as iron and zinc (Mayer Labba et al., 2022). Consequently, consumers are compelled to opt for fortified products to mitigate the risk of long-term deficiencies (Farsi et al., 2022). Furthermore, the potential occurrence of allergens and various environmental contaminants in these innovative food products or novel foods, including heavy metals, pesticides residues, microplastics, etc., poses substantial concerns regarding their enduring impact (Hadi and Brightwell, 2021; Oonicx and Finge, 2021; Bogueva and McClements, 2023; FAO and WHO, 2023; Olenic and Thorrez, 2023), the consequences of which are currently uncertain, as reiterated throughout this article. The potential occurrence of severe adverse health effects, including nutritional deficiencies or metabolic diseases with regular long-term consumption, remains a major concern for

- High protein content and amino acid profile generally considered balanced
- Contribute to the dietary fiber intake (chitin)
- Source of bioactive compounds: essential fatty acids, phospholipids, sterols, chitin
- Rich sources of both bioavailable macro- and micro-minerals
- Sources of vitamin A, D, E, and B-complex

- Limited knowledge on the technological and sensory effects resulting from insect incorporation, as well as their long-term impact on human health
- Overestimation of crude protein content (high non-protein nitrogen), and low thiamine
- Protein digestibility data remain limited to *in vitro* and animal studies
- Chitin is a potential antinutritional factor

- Highly diverse nutritional composition influenced by intrinsic and extrinsic factors
- Nourishing, sustainable and healthy source of nutrients
- Suitable for consumption as whole-food or as a fortifying ingredient

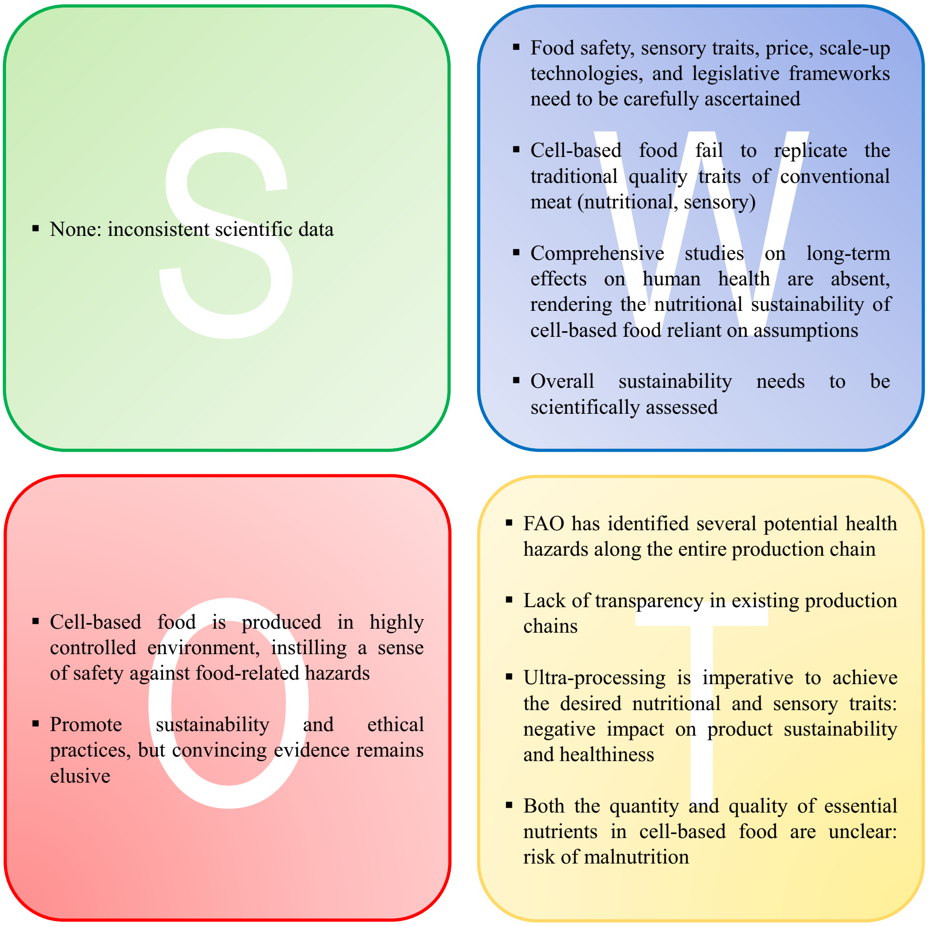
- Nutrients bioavailability can be hampered by insects antinutritional factors
- May also contain hazardous substances: microbial contamination, allergens and environmental pollutants, including pesticides, mycotoxins, and heavy metals

Figure 4. SWOT analysis related to the nutritional sustainability of the assessed insect-based meat alternatives.

the future meat alternatives (Hadi and Hardwell, 2021; Bogueva and McClements, 2023; Olenic and Thorrez, 2023). An additional potential constraint pertains to the potential misapplication of emerging technological innovations in the production of these meat alternatives. Food manufacturers should proactively endorse industrial technologies that mitigate the excessive utilization of additives or the implementation of extreme processing. UPF are progressively being regarded as hazardous by both consumers and regulatory agencies, rendering a plausible impending deceleration or setback in their market (Bogueva and McClements, 2023; FAO and WHO, 2023; Xiong, 2023).

Considering the SWOT analysis above, these meat alternatives showcase promising features. Each of them possesses unique nutritional and functional properties that should be valued rather than altered and processed solely to replicate an existing product, especially when excessive processing tends to degrade many of these distinctive characteristics. However, at present, there seems to be a prioritization of the need to replicate the familiar and beloved qualities of meat for the success of these meat alternatives, even though recreating these traits transforms whole protein-rich materials into UPF. In food production, healthiness should never be sacrificed for taste, as this does not represent a long-term sustainable solution. Food industries should, therefore, assess whether recreating the sensory properties of meat aligns with a nutritionally sustainable strategy.

In light of these challenges, the possibility of meat alternatives completely dominating the meat market remains highly improbable. Nonetheless, various proponents have made optimistic claims predicting the end of the meat market in the near future, albeit without providing conclusive evidence (Siegrist and Hartmann, 2023). Negative and inconsistent consumer-acceptance trials (Siegrist and Hartmann, 2023), as well as different societal roles related to animal farming beyond mere food production (Ederer and Leroy, 2023; Wood et al., 2023), are tangible opposing factors frequently overshadowed by the highly organized network of meat analog supporters (Leroy et al., 2023).



- None: inconsistent scientific data

- Food safety, sensory traits, price, scale-up technologies, and legislative frameworks need to be carefully ascertained
- Cell-based food fail to replicate the traditional quality traits of conventional meat (nutritional, sensory)
- Comprehensive studies on long-term effects on human health are absent, rendering the nutritional sustainability of cell-based food reliant on assumptions
- Overall sustainability needs to be scientifically assessed

- Cell-based food is produced in highly controlled environment, instilling a sense of safety against food-related hazards
- Promote sustainability and ethical practices, but convincing evidence remains elusive

- FAO has identified several potential health hazards along the entire production chain
- Lack of transparency in existing production chains
- Ultra-processing is imperative to achieve the desired nutritional and sensory traits: negative impact on product sustainability and healthiness
- Both the quantity and quality of essential nutrients in cell-based food are unclear: risk of malnutrition

Figure 5. SWOT analysis related to the nutritional sustainability of the assessed animal cell-based food products.

Conclusions

Meat alternatives have emerged as a promising and ethically conscious solution to mitigate concerns related to the growing demand for animal foods, positioned as a more sustainable option for consumers. Promoters of these alternatives often assert the imminent achievement of a meat-like nutritional and sensory profile, anticipating a transformative impact on the meat market. Despite these assertions, the current array of protein-rich materials in use has failed to authentically replicate the multifaceted properties of conventional meat. This limitation primarily stems from the intricate challenge of reproducing not only the complex matrix of meat but also its unique nutritional, functional, and sensory attributes.

In conclusion, given the current state of knowledge, it is challenging to ascertain whether meat alternatives can truly serve as a sustainable nutritional substitute. This challenge arises from the limited availability of long-term randomized studies investigating their impact on consumers' health. Meat, being an unprocessed, nourishing, and culturally significant food essential for the majority of global populations, is difficult to replace. Certainly, the permanent substitution of meat with UPF is not recommended due to the well-documented adverse health effects associated with the regular consumption of this category of food products. The intricate balance between nutritional sustainability, cultural significance, and health implications necessitates further research and consideration to guide dietary choices and promote sustainable food practices.

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