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REVIEW ARTICLE

Plant-based protein sources applied as ingredients in meat analogues sustainable production

Fontes de proteína vegetal aplicadas como ingredientes na produção sustentável de análogos de carne

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Abstract

Though obtained from vegetable ingredients, meat analogues are replacers of traditional meat products. They mimic the flavor, juiciness, and texture and look similar to their counterparts. The innovation relies on addressing nutrition, wellness, environmental, and social issues. Plant-based sources are seen as healthier and environmentally friendly for some people. Therefore, this review summarizes nutritious vegetable sources as alternative protein-based ingredients in meat analogues for sustainable development in the food production chain. A survey was conducted from January 2019 to December 2023 in three databases to find out the most used vegetable sources rich in protein, scientific journals, gaps, and legislation on this topic. The main protein-rich ingredients in the timeline publications were soybean, pea, chickpea, peanuts, oat, and isolates from these sources, besides microalgae extrudates. These raw materials add up the nutritional value and technological properties to meat analogues. Much was done in the later years concerning technology, although there are still gaps on specific legislations for plant-based products worldwide, investments in segregated plants within a meat industry and marketing, so people are more open and aware of the benefits. Concerning the outcomes of this research, it is possible to conclude that meat analogues will remain a focus, and more ingredients are prone to meet consumer demands of innovative and healthy products that go beyond the purpose of just nourishing but indeed offering extra benefits, and opening new possibilities of marketed products.

Keywords: Future food; Meat replacer; Healthy ingredient; Nutritional composition; Amino acid profile; Fatty acid profile; Phenolic compounds; Digestibility.

Resumo

Os análogos cárneos são substitutos dos produtos cárneos tradicionais, embora obtidos a partir de ingredientes vegetais. Eles imitam o sabor, a suculência, a textura e são semelhantes aos seus equivalentes. A inovação está em combinar nutrição, bem-estar, questões ambientais e sociais. Fontes vegetais são vistas como mais saudáveis e ecologicamente corretas por algumas pessoas. Portanto, esta revisão resume fontes vegetais nutritivas como ingredientes alternativos proteicos para análogos cárneos visando desenvolvimento sustentável na cadeia produtiva alimentícia. Foi realizada uma pesquisa de Janeiro de 2019 a Dezembro de 2023 em três bases de dados para se descobrir as principais fontes vegetais proteicas, periódicos científicos, lacunas e legislações sobre o tema. Os principais ingredientes proteicos encontrados na linha do tempo estipulada referem-se a soja, ervilha, grão de bico, amendoim, aveia e isolados dessas fontes, além de extrusados de microalgas. Essas matérias-primas agregam valor nutricional e propriedades tecnológicas aos análogos cárneos. Muito foi feito nos últimos anos em relação à tecnologia, embora ainda existam lacunas que dependem de legislações específicas para produtos vegetais mundialmente, investimentos em fábricas segregadas dentro de uma indústria de carne e marketing, para que as pessoas estejam mais abertas e conscientes dos benefícios. Como resultados desta pesquisa é possível concluir que os análogos cárneos continuarão em foco e mais ingredientes tendem a surgir para atender às demandas dos consumidores por produtos inovadores e saudáveis que vão além da nutrição, oferecendo benefícios extras e abrindo novas possibilidades de produtos comercializados.

Palavras-chave: Alimento do futuro; Substituto cárneo; Ingrediente saudável; Composição nutricional; Perfil de aminoácidos; Perfil de ácidos graxos; Compostos fenólicos; Digestibilidade.

Highlights

- Five-years survey summarize the most used plant-based protein sources
- Soybean is replaced by other protein sources as pea, pulses, rice, beans and lentils
- Personalized nutrition seems to be the future so that one can choose its own needs

1 Introduction

The United Nations Food and Agricultural Organization (FAO) preconizes that sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources (Food and Agriculture Organization, 2010).

Although meat analogues are well known since the 70s (Heinze et al., 1978), in the last years, they are achieving notoriety and becoming popular as a healthier and more sustainable alternative to alleviate the increasing demand for meat consumption (Fu et al., 2021; Soni et al., 2022), which is foreseen to grow in the coming years to feed 9.8 billion people by 2050 (United Nations, 2017).

The human diet without meat generally lacks nutrients. To achieve the protein needs, vegetarian people are consuming meat analogues (Singh et al., 2021). On the other hand, for meat-eaters, or flexitarians, a more attractive option would be the hybrid products, which contain both animal-based and plant-based ingredients, achieving a more sustainable approach by reducing to nearly half the meat intake (Baune et al., 2022).

Regarding the impact of meat on sustainability, scientists increasingly agree that to meet climate change goals, we must tackle the environmental impacts of animal-based food production. This was underscored at the 28th United Nations Convention on Climate Change, where over 150 countries signed the “Cop28 United Arab Emirates (UAE) Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action” (United Nations, 2024). This highlights a global recognition of the need to reform dietary practices, especially considering that the livestock supply chain contributes to 11-20% of global greenhouse gas emissions (Poore & Nemecek, 2018; Tubiello et al., 2022; Xu et al., 2021). Moreover, 83% of agricultural land is used for animal farming, which provides only 18% of calories and 37% of proteins consumed globally (Poore & Nemecek, 2018). Agriculture is the main deforestation driver, responsible for about 80% of it, notably in the Brazilian Amazon due to cattle ranching and soy cultivation (Silva Junior et al., 2020; Qin et al., 2021). Loss of biodiversity, exceeding freshwater use limits, and significant water consumption for livestock farming also raise concerns.

Addressing the climate crisis requires urgent action, given rising global temperatures. Even if fossil fuel emissions ceased immediately, emissions from the food system alone would make it hard to meet the Paris Agreement's goals. Projections suggest we may have already exceeded the carbon budget needed to limit warming to 1.5 °C, reinforcing the need for effective measures (Clark & Tilman, 2017; Harwatt et al., 2020). Accelerated glacial melt further underscores the seriousness of climate change. Collaborative efforts are essential to transition towards more sustainable food production practices, mitigating the ecological footprint of animal products for a resilient future. By transitioning soybean cultures to other sources of vegetables, we can reduce the pressure on fragile ecosystems and mitigate the environmental impact associated with deforestation. Utilizing vegetable-based co-products, for example, offers an opportunity to adopt more sustainable farming practices that minimize chemical inputs and promote soil health. Additionally, diversifying plant-based food sources beyond soy can enhance food security and resilience in agricultural systems, reducing dependence on a single crop and fostering crop rotation practices that benefit soil fertility (Silva Junior et al., 2020). Overall, the search and study of new plant sources for plant-based foods aligns with the principles of sustainable agriculture and contributes to a more environmentally responsible food system (Qin et al., 2021).

As healthier products must be low in salt, fat, cholesterol, and calories, and be safe and sustainable at the same time, they must also be rich in protein, which is one of the reasons that people nourish themselves with meat analogues. To better understand the plant-based sources, with an emphasis on proteins in the formulation of healthier and sustainable meat analogues, this review surveyed the last 5 years, out of three databases, bringing the most up-to-date literature to summarize the most used plant-based protein sources applied as ingredients in meat analogues along with the main journals that publish in the field. Therefore, we aimed to help readers with organized information on this topic.

2 Revision

2.1 A panorama of the reported studies of plant-based meat analogues

An approach was done regarding the most used vegetable-source ingredients included in the formulation of meat analogues, however focused on proteins, because it is the major ingredient in diet composition and also the nutrient of concern for most consumers. The temporal search was limited between January 2019 and December 2023, in order to gather information about the most up-to-date literature.

The research databases ScienceDirect, Scopus, and Springer were used for the literature search. After selecting the most suitable keywords related to this study, the keywords “meat” and “analogue” and “protein” were combined in the mentioned time frame, resulting in 345 documents in Science Direct, 537 documents in Scopus, and 735 in Springer. After narrowing to subject areas (agricultural and biological science, chemical engineering, and biochemistry and molecular biology), 313, 260 and 282 articles from ScienceDirect, Scopus and Springer were respectively selected. The methodology used is depicted in Figure 1. From the 855 final manuscripts evaluated, there were some repetitions or articles that did not refer to protein, which were then excluded, resulting in 117 final manuscripts.

Several commodities, mainly soybean, pea, chickpea, and peanuts, that are rich in high-quality proteins, have been reported to be added to meat analogues in order to replace meat. Figure 2 shows the main protein sources devoted to meat analogues research. The main reviews found refer to soy and pea (Ahmad et al., 2022; Cornet et al., 2020; Huang et al., 2022; Kårlund et al., 2022; Rajpurohit & Li, 2023; Sha & Xiong, 2020; Shan et al., 2023; Soni et al., 2022; Sun et al., 2021), once both seem to have an adequate amount of lysine, according to the essential amino acid pattern for an adult, recommended by the Joint WHO/FAO/UNU Experts

Consultation (World Health Organization, 2007). As it is an essential amino acid directly related to growth and is not synthesized by the human body (requiring ingestion), the consumption of lysine in the diet is extremely important, being found in vegetables (especially soy) and dairy products, but mainly in meat products. It is worth highlighting that this is commonly the first limiting amino acid in diets based on roots and/or cereals (Hodgkinson et al., 2023; Monte Singer et al., 2020). Therefore, lysine is one of the main nutrients that alternative protein producers seek to replace in traditional meat. In addition to lysine, nine other standard essential amino acids for humans are present in soybeans, such as histidine, isoleucine, leucine, methionine, phenylalanine, threonine, tryptophan, and valine (Monte Singer et al., 2020). Pulses are recently being cited among the world's most ancient commodities. Pulses including dry beans, dry peas, chickpeas, and lentils are legumes with promising applications in meat analogues (Baune et al., 2022; Mazumder et al., 2023) due to their higher protein content.

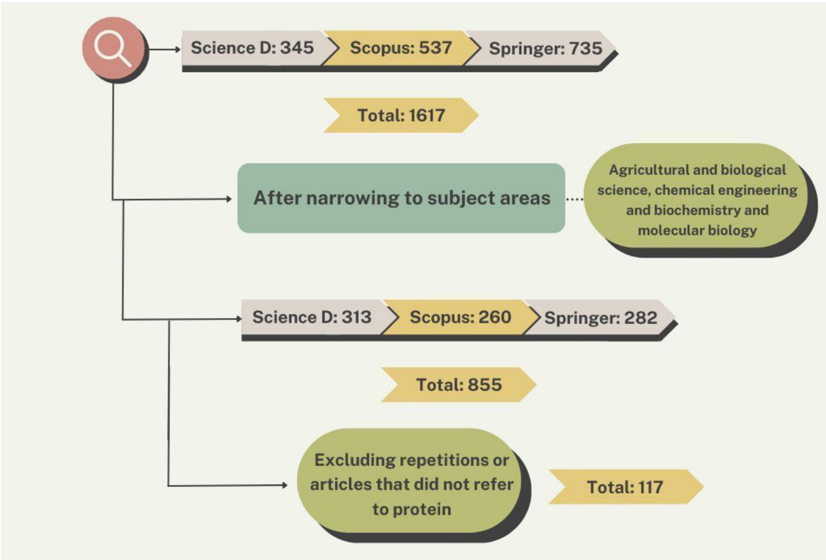

Figure 1. Methodology for article selection from three databases.

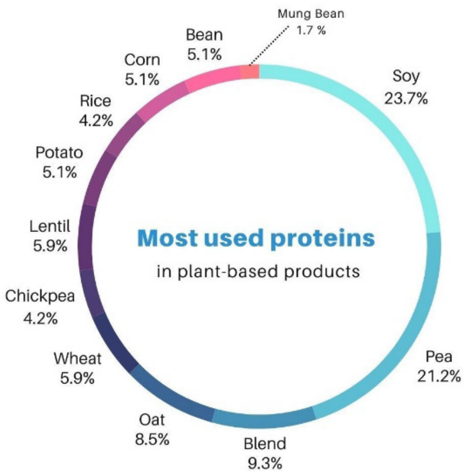

Figure 2. Most used plant-based proteins to produce meat analogues.

Protein isolates are also very common in meat analogues, made from fababean, pea, soy, and wheat gluten, which besides improving nutrition (concentration of protein and fat), also help in the formation of fibrous structures (Cornet et al., 2021), and improve mechanical properties (Dreher et al., 2021). Yellow pea and fababean protein isolates/concentrates improve functional properties (Ferawati et al., 2021), such as stabilizing emulsions and foam (Mazumder et al., 2023), while hemp protein concentrate is applied in high moisture meat analogues, replacing soybean concentrate (Zahari et al., 2020).

Other examples of ingredients/processes used in meat analogues development are cricket-soy (Kiiru et al., 2020), microalgae extrudates at 30% addition at a 60% moisture level (Caporgno et al., 2020), dry-fractionation of pea and oat proteins with more neutral sensory characteristics when protein isolates were used (De Angelis et al., 2020), and mushrooms to improve functional properties (Das et al., 2021) and also as an ingredient in 3D fiber-enriched printed snacks aimed at personalized nutrition (Keerthana et al., 2020).

Soybean press cakes (fermented okara) had a better water-holding capacity and sensory properties, with reduced hardness and oxidation when fermented with *Lactobacillus plantarum* at optimal conditions. Once texture is a pillar in the formulation of meat analogues, Ebert et al. (2021) compared texturized pea, pumpkin, and sunflower proteins, with pork meat proteins. Sunflower and pumpkin had better buffering results and less acidity, showing to be suitable as plant-based protein ingredients.

Some publications were more related to the replacement of soybean protein with other promising protein sources such as rapeseed meal (Jia et al., 2021), protein isolated rice (Lee et al., 2022), broad beans and lentils (Baune et al., 2022) and to the formulation of blended vegan meat (75.35% soya grits, 1.25% alfalfa sprout, and 22.73% wheat flour) (Sharma et al., 2022). To this end, it is necessary to consider the adaptation of agricultural practices to achieve sustainable food systems, for example, crop rotation, highlighting the benefits of tropical and subtropical conditions, especially for the cultivation of soybeans, corn, and wheat, resulting in significant improvements in crop production and soil quality, as well as pest control (Galanakis, 2024). Therefore, finding soybean alternative protein sources is the key to the production of an environmentally friendly meat analogue (Caporgno et al., 2020), including increased food security due to supply chain disruptions (Galanakis, 2024).

It is worth mentioning the physicochemical and chemical composition of food matrices are influenced by several factors such as species, cultivar, climatic conditions, soil composition, conservation conditions, and processing, among others. Anti-nutritional factors, such as trypsin inhibitors, must also be taken into account before adding an ingredient to meat analogues (Riaz & Cheewapramong, 2009).

The spray-dried microalgae biomass combined with soybean protein, which was also investigated in another work, had a better effect on the fibrillary formation of the plant-based food matrix made by Caporgno et al. (2020). This effect promotes a plant-based ingredient with less soybean and with more tenderness at the cost of reduced texture. The use of 30% *Spirulina* combined with *Lupinus angustifolia* L. protein isolate could be an alternative ingredient for meat analogues, since this combination was the best one for the extrusion processing and also led to an increment of total flavonoids and phenolic content, antioxidant capacity, and *in vitro* digestibility when compared to other ratios (Palanisamy et al., 2019).

Many researchers focused on extruding process technologies development (Caporgno et al., 2020; Kiiru et al., 2020; Leonard et al., 2020; Maung et al., 2020; Plattner, 2020; Sun et al., 2022; Wittek et al., 2021) to improve the texture of meat analogues and also techno-functional properties in the last years. Techno-functional properties, such as water solubility or water absorption capacity, should be taken into account when evaluating raw materials and designing extruded meat analogues from plant proteins (Wittek et al., 2021). Some drawbacks reported were the cooking stability for those high-moisture meat analogues and the lack of consumer acceptance tests (Maung et al., 2020). The use of pulses in developing countries is an important source of protein which is being texturized by thermal and mechanical means to make meat analogues substitutes and extenders (Teferra, 2021).

Concerning the main Journals that published research on meat analogues focused on proteins in the last 5 years, Figure 3 shows the information recovered, throughout the survey of original articles from January 2019 up to December 2023, using the combination of the words (meat AND analogues AND protein).

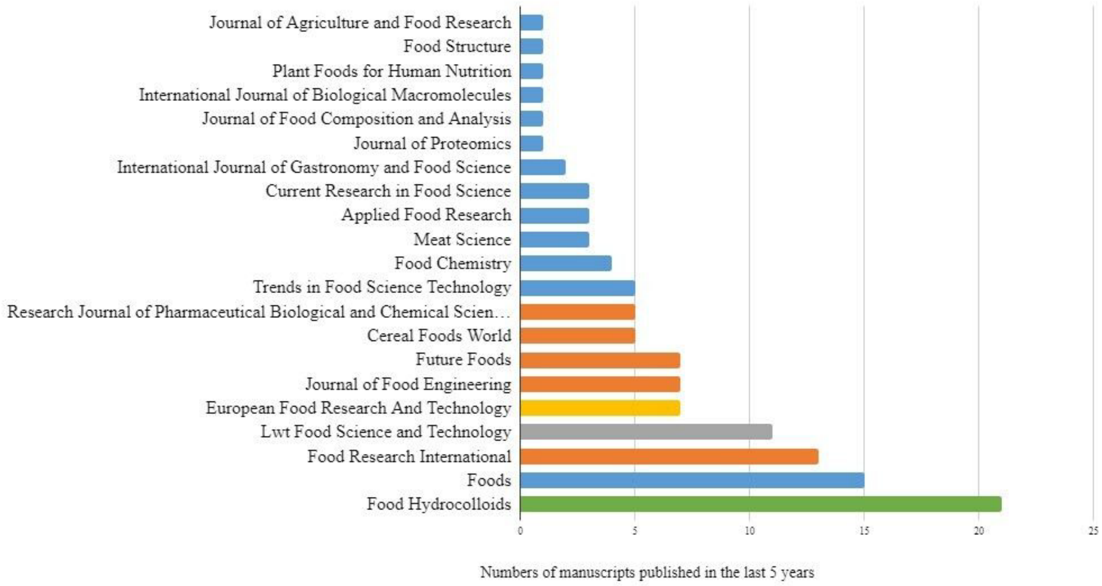

Figure 3. The number of publications within the main scientific journals devoted to meat analogues and proteins from 2019 to 2023.

The main Journals devoted to cover meat analogues focusing on proteins are Food Hydrocolloids, Foods, LWT-Food Science and Technology, Food Research International, and European Food Research and Technology (Figure 3). All these journals are situated in Europe, from where the vegetarians' movements have been ascendant.

2.2 Composition of plant-based ingredients for meat analogues, and digestibility issues

Protein is an indispensable nutrient for the human body (Sun et al., 2021; Xie et al., 2022). Concerns about keeping a balanced diet have raised the attention toward protein bioavailability and nutrition of plant-based meat analogues (Shan et al., 2023).

Although plant-based ingredients contain high-quality proteins, some amino acids are limiting, besides digestibility may be compromised (Bohrer, 2019). Also, the impact of those ingredients on texture, color, amino acid profile, and the presence of anti-nutrients and allergens must be carefully considered (Anzani et al., 2020).

The physicochemical composition, the amino acids and fatty acids profiles, and the total phenolic content of some relevant protein sources usually applied as ingredients in meat analogues are presented in Table 1.

Table 1. Proximate composition, amino acids and fatty acids profiles, and total phenolic compounds of protein sources used in meat analogues.

Proximate composition (g/100 g)	Chickpea (*Cicer arietinum* L.) from Brazil	Pea (*Pisum sativum* L. cv. Maria) from Brazil	Solvent-extracted soybean (*Glycine max*) meal from South Africa*
Moisture	7.79 ± 0.85	9.88 ± 0.84	7.68
Ash	3.15 ± 0.20	3.00 ± 0.03	6.14
Lipids	6.69 ± 0.56	2.34 ± 0.01	1.98
Proteins	18.5 ± 1.74	21.9 ± 1.53	51.18
Carbohydrates	54.0 ± 3.30	52.5 ± 0.04	[a]
Crude fiber	9.88 ± 2.11	10.4 ± 2.33	[a]

Table 1. Continued...

Proximate composition (g/100 g)	Chickpea (*Cicer arietinum* L.) from Brazil	Pea (*Pisum sativum* L. cv. Maria) from Brazil	Solvent-extracted soybean (*Glycine max*) meal from South Africa*
Acid detergent fiber	a	a	4.85
Neutral detergent fiber	a	a	7.03
Energy value (kcal/100 g)	a	a	454.28
Reference	Almeida Costa et al. (2006)	Almeida Costa et al. (2006)	Malebana et al. (2018)
Amino acids profile			
	Chickpea (JG-12) from India	**Pea (*Pisum sativum* L., cv. Specter) from USA; seeds were grown in Romania**	**Solvent-extracted soybean (*Glycine max*) meal from South Africa***
Amino acid (protein reference for adults*)**	**Indispensable amino acids (g/100 g protein)********		
Histidine (1.5)	2.34	a	2.23
Isoleucine (3.0)	3.53	4.69	3.61
Leucine (5.9)	11.43	7.82	6.39
Lysine (4.5)	**1.90**	8.08	6.08
Methionine	1.19	a	1.97
Phenylalanine	6.06	5.47	4.01
Threonine (2.3)	3.82	4.39	3.24
Tryptophan (0.6)	**0.06**	a	1.80
Valine (3.9)	4.19	5.06	4.24
Dispensable amino acids (g/100 g protein)			
Alanine	7.07	5.16	3.58
Arginine	5.20	9.46	8.77
Asparagine	5.15	a	a
Aspartic acid	a	12.28	7.33
Cysteine	0.29	a	3.20
Glutamic acid	17.30	19.91	14.58
Glycine	4.33	4.29	2.62
Proline	7.19	a	5.43
Serine	5.69	6.38	3.91
Tyrosine	0.18	a	3.99
Methionine + cysteine (2.2)	**1.48**	-	5.18
Phenylalanine + tyrosine (3.8)	6.24	8.71	7.99
Reference	Nickhil et al. (2021)	Ciurescu et al. (2018)	Malebana et al. (2018)
Fatty acids profile (%)**			
	Chickpea standard variety (Cevdet Bey) obtained from ICARDA Turkey, and grown in Turkey	**Pea (*Pisum sativum* variety cataloged as 29610), from Plant Gene Resources of Saskatoon, SK, Canada; U.S. Department of Agriculture, Pullman, WA); seeds were harvested in 2010, in Canada**	**Solvent-extracted soybean (*Glycine max*) meal from South Africa**
Lauric (C12:0)	a	a	0.55
Myristic (C14:0)	a	a	0.27
Palmitic (C16:0)	10.59	7.17 ± 0.23	17.19
Stearic (C18:0)	4.50	4.89 ± 0.14	5.13
Arachidic (C20:0)	0.31	1.09 ± 0.19	0.38

Table 1. Continued...

Proximate composition (g/100 g)	Chickpea (*Cicer arietinum* L.) from Brazil	Pea (*Pisum sativum* L. cv. Maria) from Brazil	Solvent-extracted soybean (*Glycine max*) meal from South Africa*
Behenic (C22:0)	[a]	0.51 ± 0.34	2.13
Lignoceric (C24:0)	[a]	1.26 ± 0.35	0.16
Palmitoleic (C16:1)	0.23	[a]	0.73
Oleic (C18:1, ω-9)	27.76	26.56 ± 1.94	26.54
Linoleic (C18:2, ω-6)	52.61	44.78 ± 0.89	39.24
Linolenic (C18:3, ω-3)	2.33	12.13 ± 0.58	5.33
Gadoleic (C20:1)	0.99	0.72 ± 0.09	0.16
Reference	Gül et al. (2008)	Villalobos Solis et al. (2013)	Malebana et al. (2018)
Total phenolic compounds	13.4 ± 7.2 mg GAE/100 g DW	910.69 ± 0.04 mg GAE/100 g DW	1159.5 ± 74.5 mg GAE/100 g DW
Reference	Mohammed et al. (2014)	Borges-Martínez et al. (2021)	Guzmán-Ortiz et al. (2017)

*The proximate composition of soybean meal is expressed on dry weight (DW). **Fatty acid profile expressed as g/100 g (DB) for soybean meal and relative fatty acid content for pea. ***Numbers in parentheses represent the protein reference for adults (> 18 years), according to WHO/FAO/UNU (World Health Organization, 2007). ****Data in bold type represents the limiting amino acids in each sample, according to Joint WHO/FAO/UNU (World Health Organization, 2007). [a]Data not found in the cited study. nd: not detected. GAE: gallic acid equivalent.

Chickpea, pea, and soybean have been used as sources of high-quality proteins in plant-based products and these vegetables may be also used as ingredients for developing healthier meat products. All the reported food matrices contain both indispensable and dispensable amino acids. The amino acid composition and digestibility determine the quality of a protein matrix for inclusion in the human diet as they play important roles in the metabolic pathway, as well as in the formation of other biomolecules, hormones and neurotransmitters, directly and indirectly influencing growth, maintenance and metabolism (Kumar et al., 2022). The essential amino acids: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine, need to be ingested because they are not metabolized by the human body; they are present in significant quantities in chickpea and soybean, as shown in Table 1. Pea and soybean meal seem to have an adequate amount of lysine according to the essential amino acid pattern for an adult, recommended by the Joint WHO/FAO/UNU Experts Consultation (World Health Organization, 2007). Some studies reported chickpea and grains of pea (Almeida Costa et al., 2006), as well as the soybean meal obtained by solvent extraction (Malebana et al., 2018), have a low lipid content, with linoleic and oleic as the major fatty acids (Gül et al., 2008; Malebana et al., 2018; Villalobos Solis et al., 2013). All the aforementioned matrices also have total phenolic content and proven antioxidant capacity, as it was already reported for chickpea (Mohammed et al., 2014), pea (Borges-Martínez et al., 2021), soybean (Guzmán-Ortiz et al., 2017). Currently, there is a trend towards incorporating phenolic compounds into food formulations in the food industry, which is directly linked to their antioxidant capabilities, prolonging the food shelf life, and the health benefits for the consumer (Abdullah et al., 2022; Munekata et al., 2020). As can be seen in Table 1, pea and soybean present considerable levels of phenolic compounds, and according to studies, the presence of antioxidants in meat analogues is essential to prevent the protein oxidation and rancidity of fat added to replace animal fat (Abdullah et al., 2022). It is worth mentioning that the physicochemical composition of food matrices is influenced by several factors such as species, cultivar, climatic conditions, soil composition, conservation conditions, processing, among others. Gül et al. (2008), for example, reported a significant difference in the fatty acid composition of different genotypes of chickpea, with mean values of 11.58%, 18.57%, and 47.15% for palmitic, oleic, and linoleic acids, respectively.

Soybeans are highly digestible (92-100%) and present all essential amino acids and may be an alternative protein source for people with some allergies. They are relatively low in methionine; however, they have a good lysine content (Singh et al., 2008). The presence of vital amino acids is extremely important for human growth, including lysine, which is directly related to the maintenance of the immune system and can be compared to animal protein sources (Galanakis, 2024; Shanthakumar et al., 2022). Because of all these facts, soybean is generally used as the main protein source in most meat analogues (Cui et al., 2022; Peng et al., 2021).

In addition, clear product labels containing information on the benefits of new ingredients are needed. There is room indeed for new sources of ingredients or additives obtained from nutritious plants available worldwide, mainly as analogues of animal proteins.

Besides plant-based meat analogues, hybrid products are also gaining popularity (Baune et al., 2020; Chandler & McSweeney, 2022; Ebert et al., 2021). Chandler & McSweeney (2022) developed hybrid meat burger formulations. They were made of chicken and pulses (yellow peas, chickpeas, and lentils). The latter was added to burgers at the replacement of 25%, 50%, and 75% of chicken. The chickpea and lentil incorporation did not significantly decrease the protein content of the meat analogue (18.0-18.6% protein in chickpea burger and 19.3-19.6% protein in lentil burger), which may be due to their higher protein contents (23.63% and 29.45%, respectively). However, the yellow pea addition provided less protein (12.8-15.8%).

Yang et al. (2023) compared the nutritional composition of different meat and plant-based meat analogues. The 4 formulations prepared by these authors were with pea protein, soy protein, soy protein+cheese+protein powder/solution and the last combining isolated soy protein+pea protein+wheat gluten. While in meat cuts (pork, beef), protein content varied from 26.0-32.4%, in plant-based analogues this nutrient ranges between 14.1-19.8%. Regarding macronutrients, the authors concluded that plant-based analogues did not provide as much protein as meat. One of the mentioned reasons is because additional non-protein materials such as starch and dietary fibers have to be supplemented to achieve the flavor and taste requirements.

The same authors mentioned above, also performed proportion of essential amino acids in total amino acids (EAA/TAA) and perceived that once again meat analogues showed less EAA. On the one hand, the four plant-based formulations achieved 34.8-39.3%. In contrast, beef, chicken and pork showed 44.76%, 44.78%, and 45.17%, respectively of EAA/TAA (Yang et al., 2023).

Regarding digestibility, Yang et al. (2023) also showed that protein digestibility was lower in meat analogues, despite many factors that may have influenced this conclusion, such as antinutritional factors as protease inhibitors, tannins or phytates, as well as adhesives as fibers. All these components limit the digestibility and block the hydrolysis of proteins (Yang et al., 2023).

Although plant-based products are notorious, the availability of protein ingested is different from the meat itself even if the label shows high protein content (Porta, 2020). For instance, only cow's milk, and egg have 100% availability; also 100 g beef provides 23 g protein, while 92% is bioavailable in our organism when compared to vegetable sources such as soybean, pea, chickpea, and peanut, which show the availability of respectively, 91, 89, 78 and 52%. According to Gräfenhahn & Beyrer (2024), it is unclear how the metabolites derived from plant-based products are absorbed when compared with animal-based counterparts and their implications in consumer health.

When referring to nutritional benefits of combined sources of protein-rich ingredients diverse benefits may be expected. Moreover, by considering making a tailor-made product, undesirable characteristics can be removed. For instance, if consumers are prone to pay for a meat product of low-fat content, the plant-based alternatives can resemble meat with such characteristics. Also, the industry of plant-based meat analogues supports labels (carbon footprint, etc), showing the sustainability approach; the meat industry is still hesitating to adopt these labels. This approach may happen occasionally, in some Brazilian regions.

2.3 Gaps in the development of meat analogues

Low juiciness and color, which meat consumers are familiar with, and plant-based aftertastes, are still major obstacles to market success (Sha & Xiong, 2020). As a result, research is still ongoing, thus focusing on improving consumer acceptance of meat analogues, as well as processing techniques to improve the nutritional quality of proteins and their digestibility, such as cooking, microwave, fermentation, extrusion, ultrasound, high pressure, cold plasma, and enzymatic processes (Sá et al., 2022). To obtain this similarity to the reference product, variations in additives (antioxidants and organic acids) are studied that provide stability, texture, flavor, and appearance similar to reference products. It also helps to mask unwanted flavors from the plant matrix and astringent flavors due to the presence of saponins and isoflavones in the raw material (mainly in soy protein), increasing consumer acceptability (Galanakis, 2024; Gräfenhahn & Beyrer, 2024; Sha & Xiong, 2020).

A recent study of consumer intentions to try meat analogues showed that the intention decreases with nutritional uncertainties, thus the greater the risk perceived from eating new foods, the less likely the intent to try meat analogues (Begho & Zhu, 2023).

Nowadays, the meat analogues when compared to the traditional meat present higher cost due to the inputs available locally, which makes them not available to the public, depending on the country. For instance, as the main sources of protein remain soybean and pea, for the countries where these commodities are not easily produced, the cost can be a drawback.

Higher investments must be made by the industries to start or adapt their meat facilities, in order to diverge their production and start a new one, especially when applying 3D printing or other technology to accelerate their production.

The demand for various protein ingredients and vegetable products has brought technological, sensory, and nutritional challenges to the productive sector. However, the re-utilization of by-products for consumption also entails several challenges that include negative consumer perception and stringent regulation (Ramachandraiah, 2021).

In short, the raw materials highlighted for the production of these analogues are classified as Generally Recognized as Safe (GRAS) by the Food and Drug Administration (FDA), however, the steps linked to production can modify the properties of the proteins made available to the market in the final product. Literature is still scarce regarding the effect of the processes on product manufacture, besides the quantification of non-protein compounds, traces of contaminants, plant-originated antimicrobials and antinutritional factors (such as phytic acid and tannins that act on the plant's defense mechanism) (Gräfenhahn & Beyrer, 2024). Therefore, it is imperative to create a regulatory framework for these plant-based products, which are already a global trend. According to the current understanding of the regulatory bodies, it is not possible to use the terms regulated for products of animal origin. In other words, once there is a definition of products such as hamburgers, sausages, meatballs, milk, yogurt, and so on, it is not possible to make this analogy for vegetable products (Coutinho, 2021).

A regulation (ISO 23662:2021) that specifies the definitions and technical criteria to be fulfilled for foods and food ingredients to be suitable for vegetarians (including ovo-lacto-, ovo- and lacto-vegetarians) or vegans as well as for food labeling and claims was published (International Organization for Standardization, 2021).

The Brazilian Ministry of Agriculture and Livestock, for example, published an Ordinance No. 327/2021, aiming at obtaining subsidies to encourage discussion on the regulation of plant-based products. A new Public Consultation was opened by the Brazilian National Health Surveillance Agency until the end of July, 2023 to debate Novel Foods and their ingredients. Since July, with the new Ordinance No. 831/2023, the Ministry has established a regulatory framework proposal, which includes definition, minimum quality requirements, labeling, product registration, and visual identity. Thus plant-based products must present a seal on their labeling and be registered along with the Department of Inspection of Products of Plant Origin (Brasil, 2023).

The Good Food Institute (GFI) has embraced the regulatory frame discussion of plant-based ingredients and has frequent dialogues with the government (both the Ministry of Agriculture and The National Agency of Health Surveillance). GFI, among various different actions, struggles for the construction of public policies that enable the sector's growth, aim to overcome fiscal barriers and create a favorable and stable environment for the actors involved, as well as the creation of a safe and healthy food production chain for consumers. Among the public policy actions on this front are the monitoring of legislative agendas, the promotion of regulatory impact studies, and the engagement between decision-makers from different agencies and fronts, at national and international levels (Good Food Institute, 2024).

Plant-based products come as a relevant alternative at a time when the sustainability agenda is more present than ever, but which demands greater legal certainty for those who work and are interested in working in such a promising market (Caetano, 2022).

3 Conclusion

As the global population is foreseen to keep increasing and nowadays meat production is unsustainable, the supply of animal-derived protein is predicted to be insufficient. Meat analogues can help to fulfil this demand, as they have been gaining media attention and consumers are prone to try new products, which are claimed to be environmentally friendly, e.g., diminishing gas emissions, as the animal sacrifice is avoided, also decreasing the use of land and water, as no animal will be raised and use these valuable resources. Also, vegans and flexitarians are increasing due to health concern, in part because the meat is not well seen by some of these populations, which claim that meat would cause disease, besides the necessity to sacrifice animals. Therefore, plant-based products have a welfare appeal, and their consumption is increasing day by day.

Consumer continuous demand for different healthy foods will keep driving to greener technologies as well as the development of new products, focusing on sustainability and animal welfare in the coming years. Therefore, meat analogues will continue to focus and more ingredients are prone to rise to meet consumer demands of innovative and healthy products that go beyond the purpose of just nourishing but indeed offering extra benefits and opening new possibilities for marketed products.

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