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Plant-based meat substitutes: Trends, challenges, and opportunities from a bibliometric and systematic approach

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ABSTRACT

Plant-based meat substitutes represent sustainable alternatives addressing environmental, public health, and animal welfare concerns associated with conventional meat production systems. Despite the rapid growth of the plant-based meat market, a comprehensive overview of sensory-focused research and consumer acceptance trends is still limited. Therefore, this study used a bibliometric and systematic review approach to assess the evolution and current state of sensory-related research on plant-based meat alternatives. This review followed the PRISMA 2020 guidelines and examined 121 studies published between 2019 and 2025 that examined sensory properties and consumer acceptance of plant-based burgers, sausages, and meat analogues developed from soy, pea, and wheat proteins. The bibliometric analysis showed a significant increase in publications after 2021, with Spain, China, and South Korea as the leading countries, and most publications appearing in high-impact journals focused on food science and technology. Key processing technologies ranged from established commercial methods such as high-moisture extrusion, controlled fermentation, polysaccharide gelation, and the addition of structured lipids to emerging and innovative technologies, including 3D food printing and cell cutting technology, aimed at enhancing texture and flavor profiles. Main sensory challenges identified were inadequate protein matrix cohesion, limited juiciness, and considerable difficulty in replicating authentic umami and volatile meat compounds. Consumer acceptance fundamentally depended on appearance, texture, flavor, and perceived similarity to conventional meat. Despite significant technological advances, meaningful sensory and emotional gaps persist clearly between plant-based and conventional meat products. Future research should prioritize developing novel hybrid protein matrices, optimizing lipid-protein interactions, employing omics tools and sensory modeling approaches, and integrating consumer neuroscience with sustainable communication strategies to strengthen consumer market acceptance.

1. Introduction

Climate change and the global water crisis are among the main environmental and social challenges of the twenty-first century. Currently, the food system contributes significantly to both problems, with livestock production being one of the most impactful sectors (Bidoglio et al., 2024; Jaisli & Brunori, 2024). Livestock farming is responsible for between 14 and 18 % of global greenhouse gas (GHG) emissions, as well as intensive use of natural resources, particularly water and land (Bidoglio et al., 2024; FAO, 2024). It is estimated that over 90 % of the water used in this sector is for livestock feed production, leading to freshwater depletion and putting additional pressure on already vulnerable ecosystems (Wisser et al., 2024). At the same time, from a human health perspective, diets high in processed meat have been associated with an increased risk of cardiovascular disease, type 2 diabetes, and some types of cancer (Hill et al., 2024; Shi et al., 2023;

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Wang et al., 2024), highlighting the need to move towards more sustainable and healthier eating patterns.

In this context, plant-based meat substitutes have emerged as a promising strategy for reducing dependence on animal meat (El Sadig & Wu, 2024). These products aim to mimic the taste, texture, and nutritional value of traditional meat by using plant proteins, fibers, oils, and functional additives (da Silva et al., 2024; Kyriakopoulou et al., 2021; Moss et al., 2023). However, despite the rapid growth of the sector, critical barriers to its widespread adoption remain, particularly those related to sensory perception, production costs, and highly processed formulations. Some studies have shown that protein matrix cohesion, water retention, lipid release, and the generation of meat-like aromatic compounds remain the main limitations to consumer acceptance.

Recent studies illustrate the diversity and fragmentation of methods used to improve the sensory quality of plant-based meat analogues. These approaches include replacing hydrocolloids in protein matrices (Peñaranda & Garrido, 2024) and using fermentation strategies to enhance flavor attributes (Mohamed & Ali, 2025). Other studies have explored the incorporation of natural antioxidants to improve the oxidative stability and shelf-life of products (Nguyen et al., 2025; Sirini et al., 2025). However, these studies are often conducted separately, without systematically combining sensory results or consumer responses.

Despite these specific advances, existing reviews focus mainly on extrusion technologies, nutritional profiles, or sustainability (Kyriakopoulou et al., 2021; Sha & Xiong, 2020; Szenderák et al., 2022), but few analyze, in an integrated manner, which strategies have been most effective in improving the sensory profile and consumer acceptance. Furthermore, while qualitative reviews exist in this field, there is a lack of recent bibliometric analyses that quantitatively map global research trends, collaborative networks, and emerging hotspots in the post-2020 landscape. Another key problem is that many plant-based meat substitute products are still considered ultra-processed because they use multiple gelling agents, flavorings, and texturizing agents, which affects their perceived naturalness and increases formulation costs. Identifying technological strategies capable of reducing the use of additives, lowering costs, and simultaneously improving sensory attributes is a research need that has been little explored.

The development of plant-based meat substitutes requires an interdisciplinary approach that integrates functional ingredients, emerging technologies, and sensory validation. To address the shortcomings identified in the literature, this study employs a dual approach: a bibliometric analysis to quantitatively map the scientific evolution of the field between 2019 and 2025, identifying global trends, collaborative networks, and emerging research foci, followed by a systematic review focused on technological strategies aimed at overcoming key sensory barriers and improving consumer acceptance of plant-based burgers and similar products.

2. Methodology

2.1. Data collection

The articles included in this bibliometric review were sourced from the Scopus database, selected for its extensive multidisciplinary coverage and its suitability as a single source for rigorous bibliometric analysis, as documented in previous studies. (Baas et al., 2020; Pranckutė, 2021). The search strategy was structured following the PIO approach. The Population (P) included terms widely used in the literature to describe plant-based meat products, such as “plant-based”, “plant based”, “meat alternatives”, “meat analogues”, “meat substitutes”, “meat imitation”, “vegan meat”. The Intervention (I) considered terms related to sensory evaluation, including “sensory”, “sensory evaluation”, and “sensory analysis” as well as specific terms used in instrumental and descriptive studies of sensory profile, such as “texture profile analysis” and “TPA”. These components (P AND I) constituted the mandatory search criteria. The Outcome (O) component, which included the words “consumer acceptance”, “preference”, or “liking”, was used in a complementary manner to identify studies that evaluated consumer response, without excluding research focused exclusively on descriptive sensory profiling. The search was conducted over the period 2019–2025, using the title, keywords, and abstract of the documents. A total of 614 articles were identified, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol proposed by Page et al. (2021) for the selection process and utilizing the PRISMA checklist provided in the supplementary materials. Original articles, sensory studies, technological research, and consumer analyses related to the development, physicochemical characterization, or sensory evaluation of plant-based meat analogues were included. Reviews, book chapters, and conference proceedings were excluded. During screening, articles that mentioned meat substitutes without formulating them, or research focused solely on natural preservatives without direct application in analogues and clinical studies, were also discarded. After applying the eligibility criteria, 121 studies were selected (Fig. 1).

2.2. Data processing

The bibliometric analysis was carried out using two complementary software programs. Bibliometrix, through its Biblioshiny web interface (Aria & Cuccurullo, 2017), allowed us to generate descriptive graphs that support the evolution and distribution of the analyzed literature. Annual publication trends for the period 2019 to 2025 were calculated. Likewise, a comparative graph of productivity by country was produced, allowing the identification of the nations with the greatest contributions in this field. Additionally, a ranking of the most-cited authors was generated to recognize influential researchers. The analysis also included identifying the journals with the highest number of published articles and evaluating the most productive institutions. Finally, the authors' annual productivity was analyzed using a bubble chart that combined the number of articles and citations per year, thereby visualizing the trajectories of the main contributors.

VOSviewer (Van Eck & Waltman, 2010) was used to graphically represent knowledge networks, generating a co-occurrence map based on the authors' keywords to visualize connections among recent research topics on plant-based meat. To ensure accuracy in thematic grouping, a thesaurus was incorporated to unify equivalent terms, such as animal, animals; antioxidant, antioxidants; human, humans; meat, meats; protein, proteins; texture, textures; as well as field-specific expressions such as meat analogue; plant-based meat analogues; plant proteins; and physicochemical properties. Applying this procedure reduced redundancies, homogenized vocabulary, and improved the conceptual delimitation of nodes. This analysis revealed clusters organized around central themes.

These analyses enabled characterization of the structure, dynamics, and trends of scientific production on plant-based meat products from a sensory perspective.

3. Results and discussions

3.1. Analysis of studies

The evolution in the number of publications on plant-based meat products and sensory analysis between 2019 and 2025 is shown in Fig. 2. There is a growing trend, starting in 2022 and peaking in 2025, with 53 articles published, indicating an intensification of scientific interest in this topic. This increase aligns with the broader adoption of key technologies, such as high moisture extrusion (HME), which is one of the primary processing methods for creating meat analogs with more realistic fibrous structures and enhanced sensory qualities (Dekkers et al., 2018; Du et al., 2026; Kyriakopoulou et al., 2019). This growth is also connected to a focus on reformulating foods with an emphasis on health and sustainability following the COVID-19 pandemic, which increased

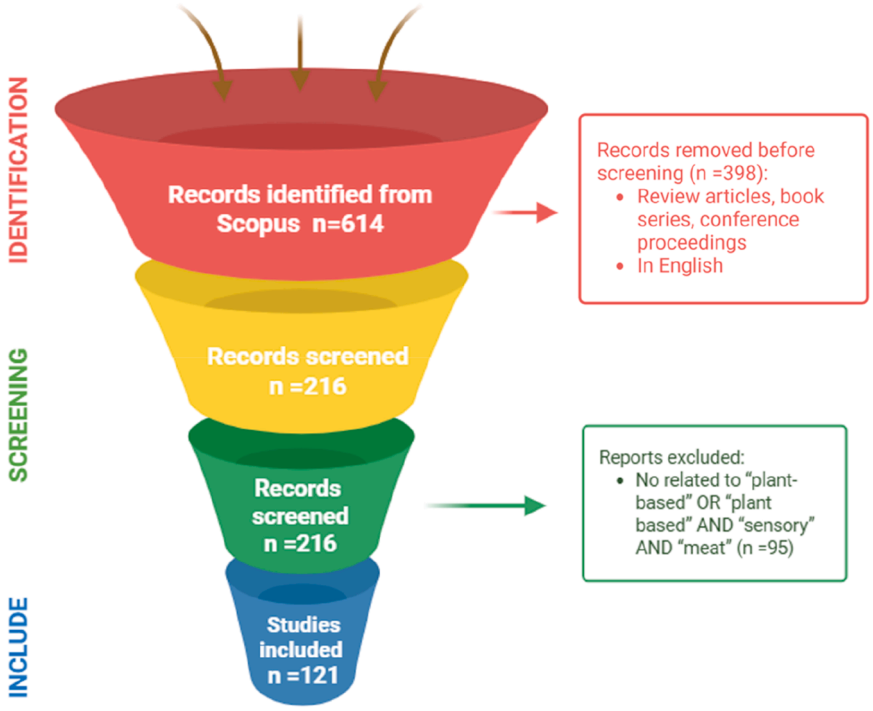


Fig. 1. PRISMA-based flowchart for study identification and selection (Page et al., 2021).

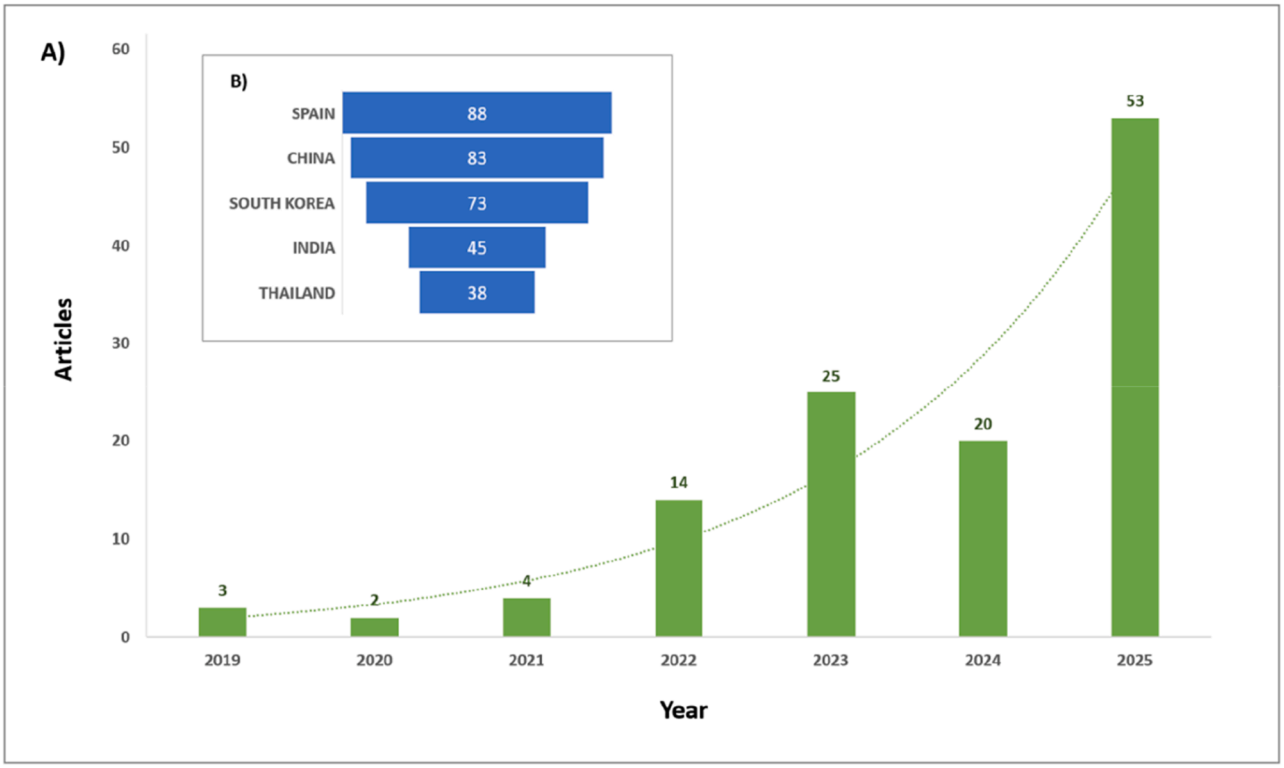


Fig. 2. Annual evolution of the number of articles (A) and main contributing countries in scientific production (B).

scientific interest in alternative proteins and more resilient food systems (Galanakis, 2020; Xavier et al., 2025).

Spain ranked first in publication volume, with 88 contributions, followed by China, South Korea, India, and Thailand. Spain's leadership could be related to the strong impetus of European research and innovation policies focused on sustainable food systems and alternative proteins, promoted through framework programs such as Horizon 2020 and Horizon Europe (European Commission, 2021). The total number of contributions per country exceeds the total number of articles, as a single manuscript may include researchers with affiliations in multiple countries.

3.2. Most cited articles

The number of citations is a key indicator of an article's academic influence. Analyzing the most cited works is essential for identifying the main research trends and the authors or teams with the greatest impact in establishing this emerging field. Fig. 3 displays the 10 most-cited articles among the 121 analyzed, highlighting contributions that have significantly influenced the field of plant-based meat products with a sensory focus. De Angelis et al. (2020) lead the list with 111 citations, closely followed by Kamani et al. (2019) with 110 citations. Both concentrate on developing and physicochemically characterizing meat analogues made from plant matrices. Next, Bakhsh A. has two high-impact publications, solidifying his role as a leader in the area. Similarly, Grasso S. has contributed from the perspective of consumer sensory perception, while Caputo V. offers important economic insights into willingness to pay for meat analogues. Meanwhile, Flores M. has addressed flavor compounds, Kaczmarska A. focuses on textural and juiciness characteristics, Ali M. researched the use of phenolic extracts from plant by-products to enhance oxidative stability, and Shen Y. focuses on optimizing protein matrices through structuring and heat treatment technologies, showcasing the variety of approaches that enhance this emerging field.

3.3. Main scientific journals in the study

Fig. 4 shows the main sources of publications on plant-based meat analogues. The 10 journals account for 55.4 % of all publications in scientific media specializing in food science and technology. The journal Foods leads the way with 22 articles, covering physicochemical properties, sensory evaluation, and the formulation of new foods. The journals Food Hydrocolloids and LWT, each with 11 articles, both focus on the functionality of proteins, polysaccharides, and emerging technologies. Food Chemistry contributes five publications, highlighting studies of volatile compounds, chemical reactions, and sensory mechanisms associated with the taste and aroma of products. Applied Food Research and Food Research International, with four articles each, focus on advanced experimental research related to ingredient interaction, structural stability, and key technological properties. Similarly, Food Quality and Preference, with three articles, emphasizes consumer sensory perception, preference studies, acceptance, and psychological factors. The journal Meat Science, featuring three articles, includes comparative evaluations of animal meat and plant-based analogues, examining structure, texture, water retention, and the mechanisms that determine quality. Finally, Current Research in Food Science and European Food Research and Technology, with two articles each, address applied approaches to ingredient characterization, structuring processes, and technological improvements. This reflects the thematic focus in high-impact journals.

3.4. Distribution of publications by institutional affiliation

Institutional analysis shows that scientific production is concentrated in a group of universities and research centers, which together account for 155 institutional contributions (Fig. 5). Asia and Europe clearly dominate as the leading regions. In Asia, Konkuk University and Jiangnan University stand out, with 23 and 22 publications, respectively, both specializing in biotechnology, food science, and bioactive compounds. They are followed by Mae Fah Luang University with 18 publications, focusing on natural products and bioprocesses. In Europe, Wageningen University & Research and the University of Extremadura have 18 and 15 articles, respectively. Their lines of research cover food technology, sustainability, analytical chemistry, and nutrition, consolidating Europe's role in the study of agri-food systems and functional compounds. Jinju has 14 publications and contributions in microbiology, fermentation, and functional foods.

The Hospital del Mar Research Institute of Spain, with 12 publications, introduces a biomedical approach from the perspective of metabolism and public health. America has a more limited participation, represented by Kansas State University and the State University of Maringá, both with 12 publications. These institutions contribute to

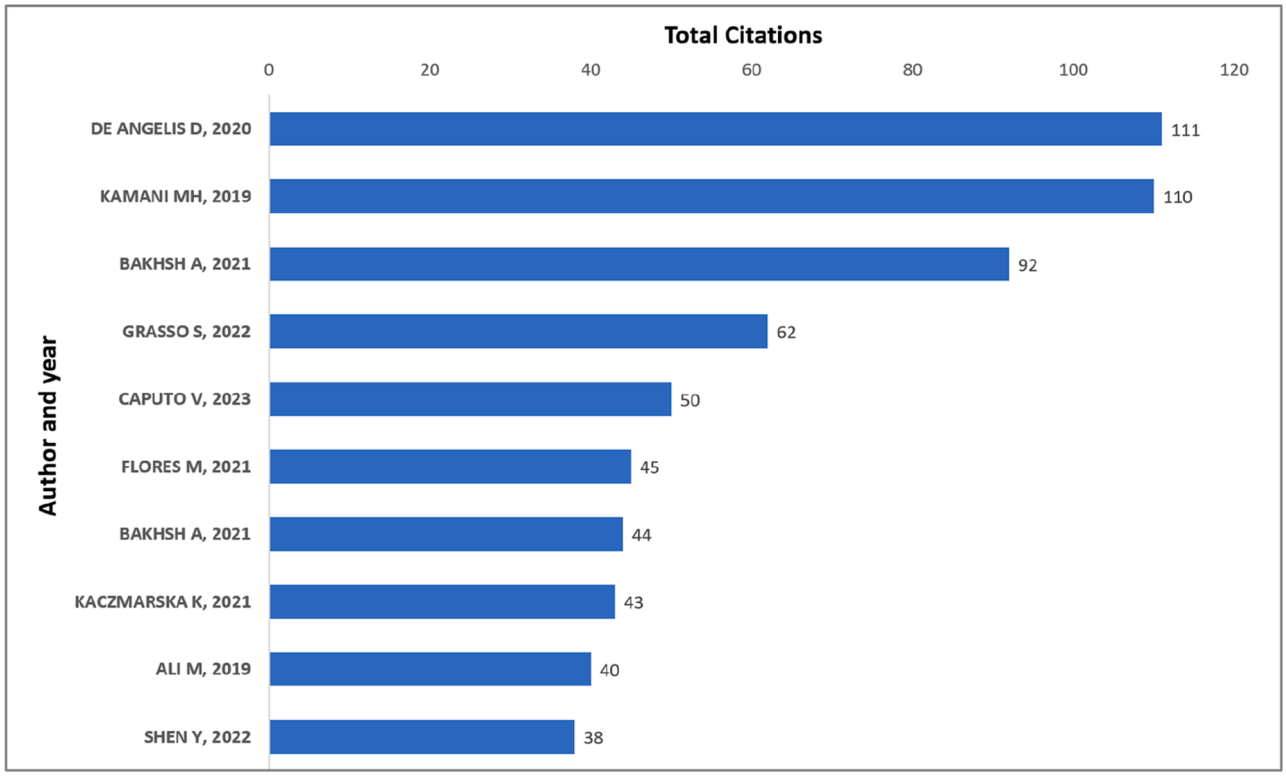


Fig. 3. The top ten articles with the highest number of citations.

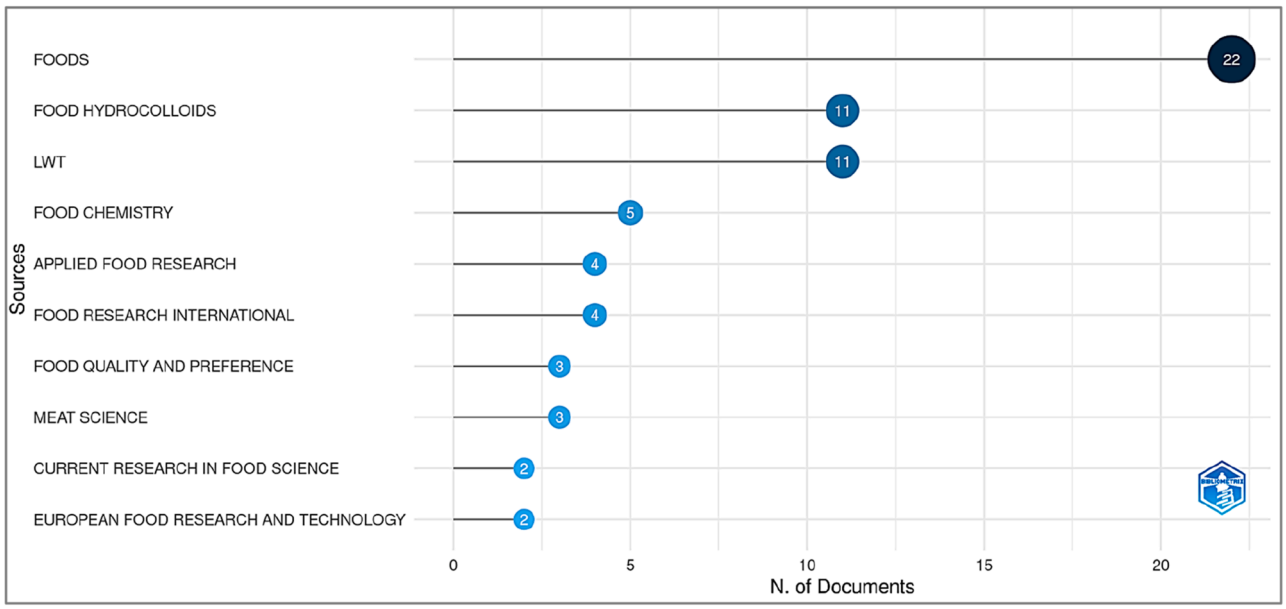


Fig. 4. Scientific journals with the highest number of publications related to plant-based meat from 2019 to 2025.

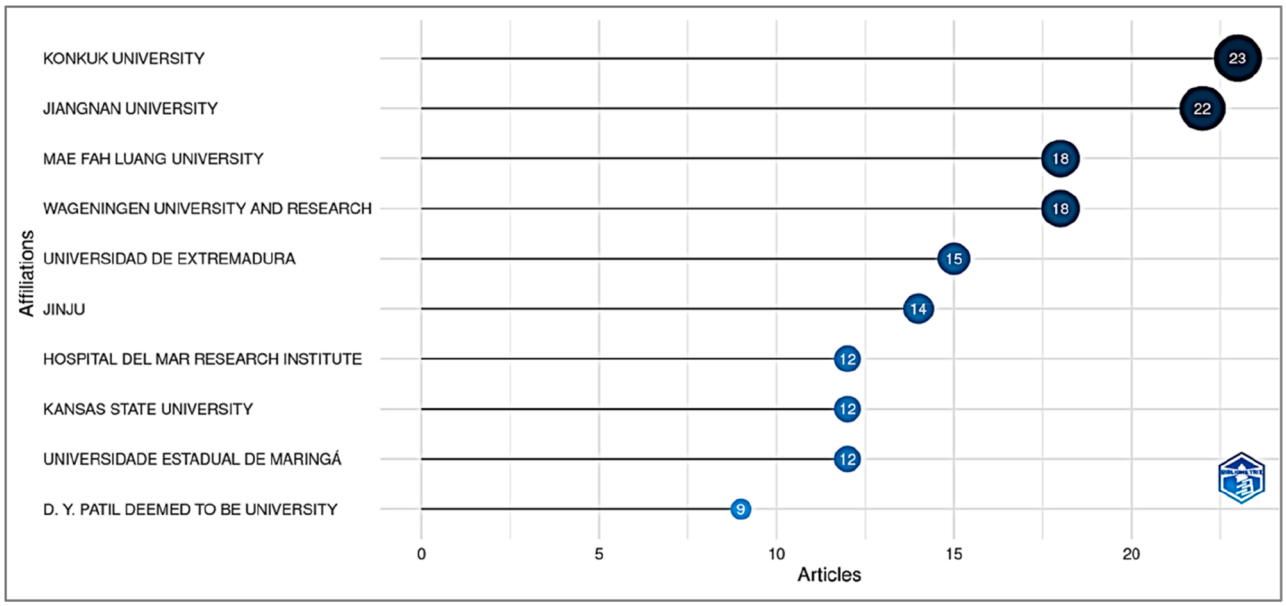


Fig. 5. Most relevant institutional affiliations in research on plant-based meat analogues from 2019 to 2025.

research on food safety, process engineering, and plant biotechnology. D. Y. Patil Deemed to Be University (India), with nine publications, researches natural products and pharmaceutical-oriented biosciences.

3.5. Author's production

Fig. 6 illustrates the evolution of productivity among the most relevant authors between 2021 and 2025, showing both the number of articles and the impact measured in annual citations (TC per Year). Each line represents an author's trajectory over time, and the circles indicate their annual scientific output and impact measured in citations.

Authors Bakhsh A., Hwang Y.-H., and Joo S.-T. stand out as the most productive researchers and have consistent trajectories over several years. Their contributions focus on the physicochemical, textural, and sensory characteristics of plant-based meat analogues. Authors such as Rawdkuen S. and Ketnawa S. began publishing in 2023, focusing on the use of fungi and textured vegetable proteins to improve the structure, stability, and sensory acceptance of plant-based meat substitute foods. In the more recent years of 2024 and 2025, contributions from González-Mohíno A., Belloch C., Han J.H., and Han S.G. address topics such as fermentation, sensory perception, rheology, and the formation of aromatic compounds.

3.6. Keyword co-occurrence network

Fig. 7 presents a co-occurrence map of terms extracted from the titles, abstracts, and keywords of the articles. This analysis shows the multidisciplinary thematic structure of the literature on plant-based meat analogues, with connections among technological, sensory, nutritional, and consumer-perception aspects. Four clusters consisting of 75 nodes were identified. The blue cluster with 19 nodes, which groups words such as chemistry, lipid oxidation, emulsion, gels, food storage,

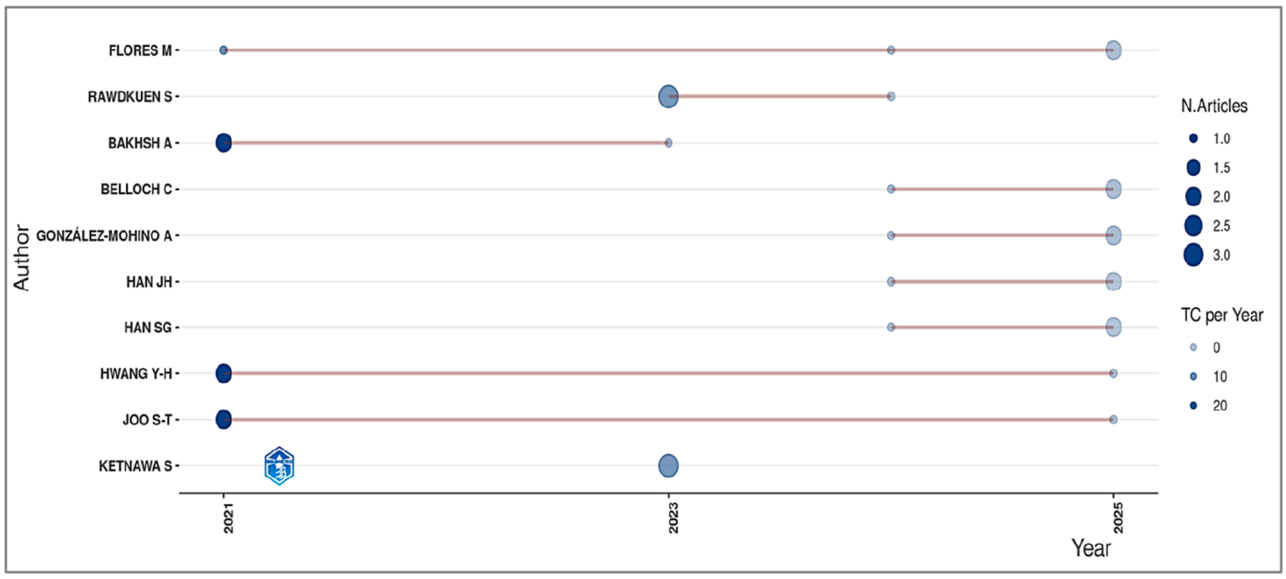


Fig. 6. Productivity and impact of leading authors in the field of PBMAs from 2019 to 2025. The size of the dark blue circles represents the number of articles published by each author, while the light blue circles indicate the annual impact measured in citations, Total Citations per Year (TC per Year).

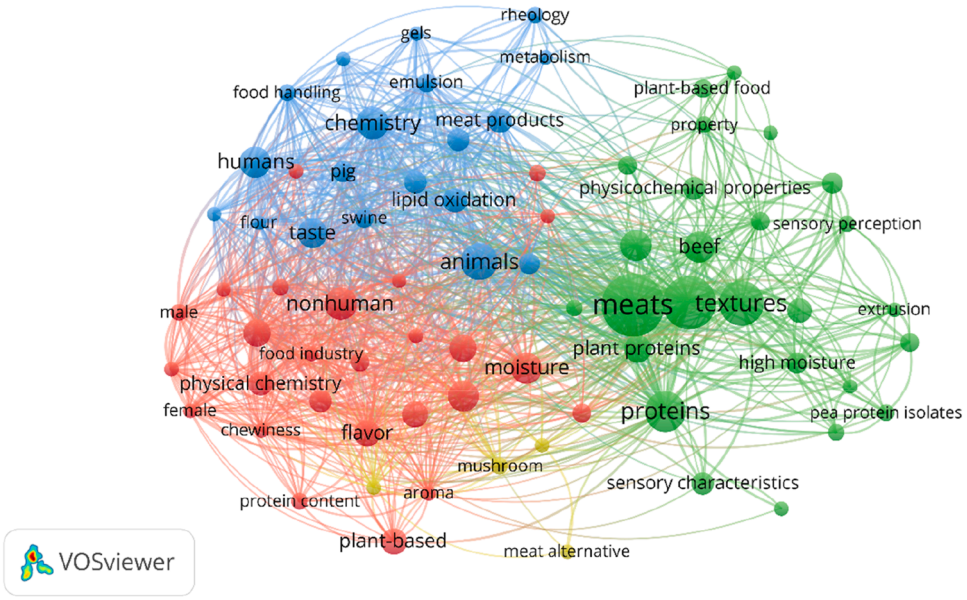


Fig. 7. Co-occurrence map generated from the titles, abstracts, and keywords of the articles analyzed from 2019 to 2025.

and taste, represents a line of research associated with "hard science" and focuses on the physicochemical stability, deterioration mechanisms, and functional properties of the ingredients used. This cluster represents a key stage in the field's development, concentrating on understanding the molecular and technological processes that support product formulation. The red cluster, comprising 26 nodes and centered on terms such as plant-based, sensory evaluation, flavor, pH, instrumental analysis, chewiness, and physical chemistry, is mainly associated with "consumer science," focusing on acceptance, sensory experience, and emotional responses to meat analogues. This thematic structure suggests a gap between technological development focused on product formulation and stability and its evaluation from a sensory and consumer perspective, a recurring obstacle to the successful adoption of innovations in the market.

The green cluster with 26 nodes, comprising terms such as meats, meat analogues, proteins, plant proteins, physicochemical properties, extrusion, fermentation, and food ingredients, serves as a bridge between the two approaches, integrating formulation and processing strategies with structural and sensory attributes. This cluster reflects a phase of maturation in the field, aimed at translating technological advances into more sensorially acceptable products. The yellow cluster, composed of 4 nodes and terms such as meat alternative, mushroom, chickpea, and sausage, represents an emerging line focused on exploring alternative ingredients, still limited in volume but with potential to diversify the protein matrices used in plant-based meat analogues.

From a broader perspective, this thematic structure not only reflects the internal evolution of the scientific field but also aligns with global health and sustainability frameworks. In this sense, the four clusters reflect the global priorities established by the World Health Organization, which promote reducing saturated and trans fats and increasing consumption of fruits, vegetables, and legumes as central components of a healthy diet (WHO, 2020). These clusters are also aligned with the

global food transformation scenarios described by the Food and Agriculture Organization of the United Nations, highlighting that diversified, plant-based diets are essential for both population health and the sustainability of food systems (FAO & WHO, 2019; FAO, 2020).

3.7. Topic areas and main findings

Of the 121 studies, seven thematic areas were identified based on product type (Fig. 8). The classification relied on analyzing the abstract, methodology, results, and conclusions. In some instances, the full text was reviewed when the focus was unclear.

Beyond classification by product type, several of the identified thematic areas share common structuring principles. In particular, the development of muscle-like fibrous textures across different product categories relies on shear-driven texturization strategies. To facilitate the interpretation of the complex processing approaches discussed in Sections 3.7.2 and 3.7.4. Fig. 9 presents a schematic representation of the main texturization routes, highlighting high-moisture extrusion and shear cell processing as converging technologies for fibrous structures formation in plant-based meat analogues.

3.7.1. Hamburger and patties

Research shows that juiciness and meaty flavor are the most important sensory qualities affecting the acceptance of alternative burgers (Table 1). Hybrid products that combine animal and plant proteins often reach acceptance levels similar to those of traditional beef burgers, especially in blind taste tests. However, providing ingredient information is crucial, especially when consumers are aware that a product contains plant-based ingredients, as this can lead to lower acceptance among certain groups. Meanwhile, texture, including softness, cohesion, and hardness, remains a key area of innovation, achieved through the use of legumes, mushrooms, and plant fibers that improve the structure and mouthfeel of meat alternatives. Below are some articles on this topic (Table 1).

3.7.2. Whole-cut analogues

The whole-cut analogues area focuses on research aimed at replicating the muscle structure and juiciness of animal meat using high-pressure methods, extrusion, or controlled gelation. Table 2 shows some studies related to this subject.

The combination of plant proteins such as soy, peas, gluten, and oats with vegetable fats and polysaccharides enables the production of matrices with fibrous, cohesive, and chewable textures that approximate the structural characteristics of meat. However, technological challenges remain, including optimizing water retention and protein network stability, as well as sensory challenges in replicating meat flavor and achieving the right balance between hardness and softness. Emerging technologies such as high-pressure processing (HPP) and HME have demonstrated substantial advances in producing restructured products that are more faithful to meat, with high potential to improve the acceptability of plant-based products.

3.7.3. Sausages

The sausages category is undergoing a gradual transition towards hybrid and 100 % plant-based formulations, driven by reductions in animal fat and additives such as nitrites. The most commonly used technological strategies include vegetable oils (corn and olive), textured proteins (soy, pea, and peanut), and controlled fermentation to reproduce the texture, color, and aroma typical of traditional sausages. Sensory-wise, hybrid products maintain acceptance comparable to meat products, while 100 % plant-based products present challenges in terms of flavor intensity and firmness. However, innovations such as oleogels and natural flavors improve their perception.

Studies point to functional and sensory developments in plant-based sausages, with fermentation technology and lipid restructuring key to achieving equivalence with traditional products. Table 3 presents some studies related to this area.

3.7.4. General formulation and processing studies

The general formulation and processing studies thematic area focuses on improving the physical, sensory, and structural qualities of products made from plant proteins, such as soybeans, peas, and legumes, as well as from alternative sources, such as mushrooms and agro-industrial by-products.

Research indicates a trend toward “clean label” formulations with less processing, fewer synthetic additives, and increased nutritional and functional value. On the sensory level, modern analogues achieve fibrous textures and juiciness similar to meat, though they still fall short in aroma and umami. The inclusion of oleogels, modified proteins, and advanced extrusion techniques represents significant progress toward achieving sensory similarity with traditional meat. Table 4 highlights some studies related to this area.

3.7.5. Croquettes, snacks, and nuggets

The Croquettes, snacks, and nuggets thematic area focuses on studies aimed at improving the texture, appearance, and acceptance of breaded

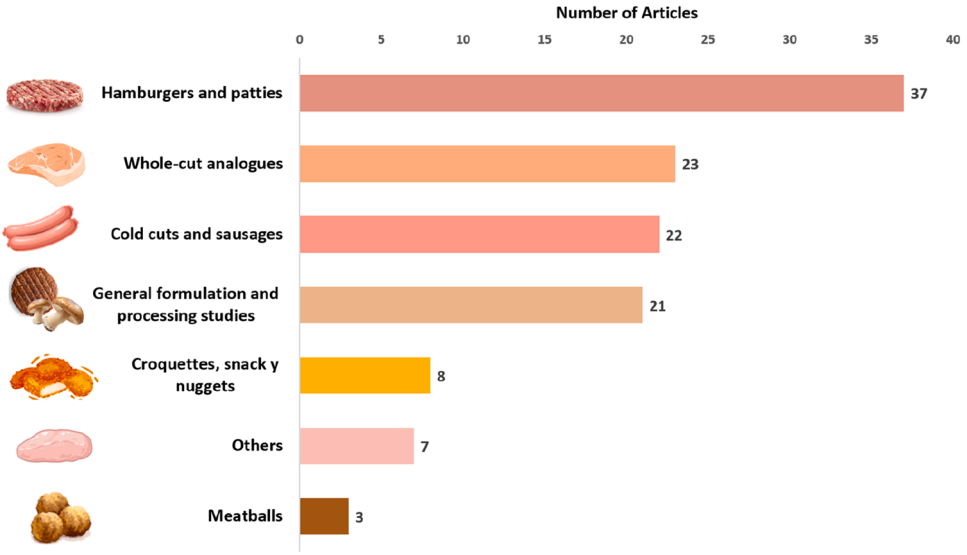


Fig. 8. Topic area of plant-based meat.

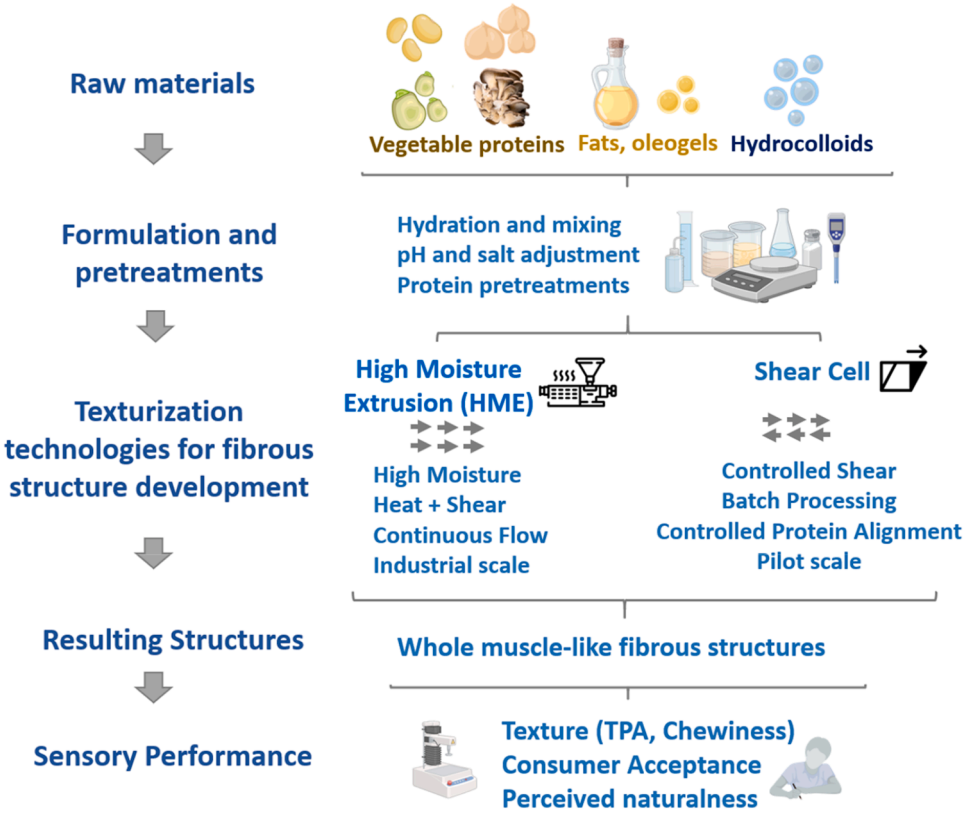


Fig. 9. Schematic representation of shear-based texturizing strategies, including HME and shear cell processing.

Table 1
Studies on burgers and patties.

Product type	Key finding	Sensory results	Reference
Vegetable burgers made from peas and soybeans with fructooligosaccharides (FOS) as a binding agent.	FOS enabled reducing the use of synthetic binding agents while maintaining cohesion.	Similar acceptability to the control; slightly softer texture.	(Peñaranda & Garrido, 2024)
Burgers with insects and vegetables (soy, seitan).	Viable formulation with good stability and texture; shelf life 7 days.	Minor sensory differences between treatments; critical texture.	(Ardila et al., 2023)
Plant-based patties, Textured Vegetable Protein (TVP), and Textured Isolated Soy Protein (T-ISP) with methylcellulose.	3 % methylcellulose improves the cohesion and juiciness of the patties	Values greater than 7 for Concentrated Textured Vegetable Protein plus 3 % Methylcellulose.	(Bakhsh et al., 2021)
Clean-label burgers made with banana peels or natural fibers.	50 % banana peel improves texture and sustainability.	Medium-high preference; darker color but acceptable.	(Issara et al., 2024)
Hybrid beef burgers (40 % plant-based, 60 % meat).	Well-regarded hybrids; plant-based information reduces meat-eaters' preferences.	High acceptance in blind tests; no significant differences.	(Grasso et al., 2022)
Patty reconfigured with hydrogel emulsion (vegetable fat)	Successful fat replacement using soy emulsions or hydrogel; no loss of juiciness.	Meat scored highest, but hybrids showed a balanced profile.	(Janardhanan et al., 2022)
Plant-based analog with Vicia pea protein	High protein content and low in carbohydrates; good emulsifying capacity.	Firm texture, neutral flavor, good acceptance.	(Hatamikia et al., 2019)
Plant-based analogue with modified pea protein (PGG)	PGG reduced cooking losses by 20 % and increased juiciness.	Softer texture preferred by older adults.	(Shen et al., 2022)

FOS = Fructooligosaccharides, TVP = Textured Vegetable Protein, T-ISP = Textured Isolated Soy Protein, PGG = Protein Gellan Gum.

or fried products made from vegetable proteins. The most common strategies include the use of textured fungi, agricultural by-products such as cashew and tomato pomace, and hybrid formulations to preserve juiciness and flavor.

Sensory-wise, consumers still perceive differences compared to traditional chicken, especially in terms of fiber and vegetable aftertaste. However, overall acceptability has improved thanks to advances in binders, oils, and extrusion processes. These products also stand out for their functional profile and sustainability, with the potential to replace meat snacks with a high environmental impact. Table 5 presents some studies related to this area.

3.7.6. *Meatballs*

Studies in the Meatballs subject area (Table 6) emphasize the effort to balance texture, juiciness, and oxidative stability in molded vegetable or hybrid products. Replacing meat with vegetable proteins or agro-industrial by-products such as banana peel or cabbage has yielded positive results in functionality and sensory acceptance, along with improvements in dietary fiber, water retention, and lipid stability. These advancements reinforce meatballs as a key experimental model for assessing the overall quality of meat analogs in plant-based research.

Table 2
Studies on reconfigured meat.

Product type	Key finding	Sensory results	Reference
Restructured meat analogues with plant proteins (soy, pea, gluten)	A model was established to predict the minimum texturization temperature and improve process efficiency.	Well-textured samples obtained better sensory scores for firmness and chewiness.	(Högg & Rauh, 2023)
Soy protein matrix with vegetable fat and alginate	Use of freezing and calcium to generate porosity and a multilayer structure.	Preferred texture compared to conventional soy analogues; more similar to animal meat.	(Kobayashi et al., 2022)
Hybrid burgers (70 % meat, 30 % vegetables)	Replacing 30 % of the protein with TVP maintained acceptable color and texture.	High acceptance; potential transition product.	(Baune et al., 2023)
Fibrous bean and pea analogues using HME	50:50 blends improve fiber structure and reduce bitterness.	Highly acceptable due to its gummy texture and lack of bitterness.	(Knaapila et al., 2024)
Reformulation of restructured meat with textured mushrooms	Fungal TVP exhibited properties comparable to those of commercial TVP.	High acceptability due to natural "umami" flavor and chewy texture.	(Ketnawa & Rawdkuen, 2023)
Meat analogues made from textured vegetable proteins (soy, chickpea, and pea) subjected to dry heat pretreatment	At 120 °C, better gelation and water absorption capacity were observed without impairing functionality. At 160 °C, functionality decreased with increasing density, and the product darkened.	It was noted that controlled denaturation at 120 °C promotes the formation of more homogeneous structures and textures, potentially making them more palatable.	(Pennells et al., 2024)
Vegetable pork rinds made with soy protein isolate, soybean oil, $NaHCO_3$, sweet potato starch (SPS), and konjac glucomannan (KGM)	The appropriate addition of SPS (40 %) and KGM (0.4 %) significantly improved the gel's hardness, cohesion, and chewability. The micrographic structure showed a more compact and stable network.	The formulations with 40 % SPS and 0.4 % KGM were most similar to natural pork skin in texture, appearance, and mouthfeel, achieving high sensory similarity to the meat product.	(Zhang et al., 2022)

HME = High-Moisture Extrusion, TVP = Textured Vegetable Protein, SPS = Sweet Potato Starch, KGM = Konjac Glucomannan.

Table 3
Studies on sausages.

Product type	Key finding	Sensory results	Reference
Hybrid fermented sausages (50 % animal with pea vegetable protein)	The combination of animal and vegetable protein improves the nutritional profile without affecting the texture.	The products were generally well received, standing out for their balanced aroma, good juiciness, and slightly milder flavor than 100 % meat sausages.	(García-Solivelles et al., 2025)
Fermented vegetable sausages (textured peanut protein 25 % to 100 %)	Increased vegetable protein can modify flavor and texture, with a high functional potential.	Moderate acceptance; differences in taste and color compared to the meat reference.	(Li et al., 2025)
Vegetable salami-style sausage	A fibrous structure similar to that of dry sausage was achieved; binder content affects cohesion.	Acceptable texture, but less firm than the meat version.	(Herz et al., 2023)
Dry-cured fermented plant-based sausages	Differences in water activity and texture; similar oxidation profile.	Lower acceptance of plant-based products due to less intense texture and flavor.	(Martín-Miguélez et al., 2025)
Hybrid and plant-based bacon (nitrite-free)	Distinct sensory profile; nitrite-free does not affect acceptability.	Plant-based bacon is less "smoky," but visually acceptable.	(Melios et al., 2024)
Sausages with vegetable oil and artichoke flour replacing animal fat	Decrease in saturated fat and increase in fiber	No significant differences in taste compared to the control, softer texture.	(Zhu et al., 2020)
Goat sausages with vegetable fat (corn oil, palm oil, or margarine)	Total replacement of animal fat with vegetable oils.	Sausage with corn oil was the most acceptable in terms of sensory properties.	(Domingo et al., 2023)
Sausage meat partially replaced by plant proteins	80–100 % replacement is feasible without loss of stability.	High acceptance in color and texture, and good commercial potential.	(Kamani et al., 2019)

4. Current and future challenges

The advancement of plant-based meat analogues requires integrating food science, biotechnology, biomaterial structuring, and sensory neuroscience. The main strategies identified and aligned with the technological and sensory challenges that still persist are:

4.1. *Technologies for improving protein matrices*

Protein matrices are the structural basis of meat analogues, and their ability to reproduce fiber structure, internal cohesion, and juiciness depends on the physicochemical mechanisms generated during processing. HME is a dominant technology that enables protein alignment, controlled denaturation, and microfiber formation through shearing and thermal gradients. Studies have shown that combining pea and soy proteins with polysaccharides such as fibers or hydrocolloids improves elasticity and water retention (Barnés-Calle et al., 2024; Ge et al., 2025; Knaapila et al., 2024).

The application of pressure has been explored as a complementary technology to improve the structure of protein matrices. In vegetable and hybrid burgers, pressure treatment has been shown to improve internal cohesion, water retention, and firmness, reproducing typical meat properties without resorting to synthetic additives (Janardhanan et al., 2022).

These technologies are essential for overcoming sensory limitations such as low cohesion, excessive hardness, or insufficient juiciness. An emerging solution involves combining HME with enzymatic or fermentative pretreatments that improve protein functionality prior to extrusion.

However, from a future perspective, alternative technologies are gaining relevance that could complement or, in certain contexts, overcome the limitations of HME. In particular, shear cell technology enables more precise control of shear and protein alignment under quasi-static

Table 4
Studies on meat analogues.

Product type	Key finding	Sensory results	Reference
Plant-based meat products	Consumers with low meat attachment (LMA) showed greater overall acceptance, aroma, and flavor than those with high meat attachment (HMA).	LMA consumers appreciated the aroma and vegetable flavor attributes more, while HMA consumers penalized the lack of "meaty flavor" and fibrous texture. The desired "meat-likeness" varied according to the level of attachment to meat.	(Kim et al., 2024)
Meat analogues made with 10 % fermented or hydrolyzed soybean meal.	Fermentation and enzymatic hydrolysis of soybean meal improved water and oil retention capacity, reduced protein oxidation, and provided high-quality fiber and protein.	Analogues with fermented soybean meal were the most acceptable in terms of sensory properties.	(Razavizadeh et al., 2022)
Plant-based meat substitute enriched with soy protein, sacha inchi, quinoa, perilla, and Amaranthus dubius extract.	The optimal formulation included 33 % soybean, 40 % sacha inchi, 20 % wheat flour, 5 % quinoa, and 2 % perilla, with 0.1 % sodium alginate as a stabilizer. The addition of 0.5 % concentrated extract of A. dubius.	Older adults rated the formulation with 0.5 % extract as more acceptable, highlighting its smoothness, cohesion, and balanced flavor.	(Putthawan & Chaiso, 2023)
Chicken analogues with combinations of young jackfruit (30–50 %), wheat gluten (10–15 %), and soy protein isolate (1–2 %).	The increase in jackfruit increased moisture and gloss, but reduced hardness and chewability.	The optimal formulation (40.64 % young jackfruit, 20.32 % wheat gluten, and 1.35 % soy protein isolate) achieved the highest sensory acceptability.	(Taikerd & Leelawat, 2023)
Vegetable meat analogues made from soy and gluten, supplemented with 1 to 7 % *Haematococcus pluvialis*	The addition of *H. pluvialis* significantly improved color, imparting red hues similar to meat. It also increased the content of volatile compounds.	Levels of 3 % and 5 % microalgae achieved the best sensory balance, with smooth texture, attractive color, and meat-like aroma. Concentrations of 7 % negatively affected viscosity and structure.	(Liu et al., 2023)

LMA = Low Meat Attachment, HMA = High Meat Attachment.

conditions, facilitating the production of more customizable fibrous structures closer to whole-muscle structures. Likewise, 3D food printing offers innovative opportunities to precisely control internal structure, porosity, and fiber orientation, enabling adaptation of textural properties to specific product or consumer requirements. These emerging technologies are becoming key tools for developing the next generation of plant-based meat analogues.

Table 5
Studies on croquettes, snacks, and nuggets.

Product type	Key finding	Sensory results	Reference
Chicken-style vegetable nuggets	Consumers clearly differentiate plant-based nuggets from the control; texture and flavor are the main challenges.	Plant-based nuggets are perceived as more fibrous, with a legume aftertaste; average acceptability.	(Ettinger et al., 2022)
Hybrid croquettes with tomato pomace	Incorporating 1–7 % bagasse improved fiber and water retention.	Firmer texture; good overall acceptance.	(Islamova et al., 2025)
Vegetable croquettes made with 30 to 50 % cashew bagasse fiber, combined with soy protein.	Formulations containing 30–40 % fiber showed excellent technological performance.	Croquettes containing up to 40 % fiber were well received for their sensory characteristics, with a pleasant texture and balanced flavor. The use of 50 % fiber resulted in an intense residual cashew flavor, reducing preference.	(Saldanha et al., 2025)
Beef-style vegetable cubes made from pea protein isolate (PPI) texturized by wet extrusion, with 15 % black bean, chickpea, or fava bean flour added.	The addition of legume flours significantly reduced the hardness of the extrudate and increased the degree of fiber content by 16 %.	The formulation with a 15 % flour blend achieved the highest sensory score, with color, flavor, and texture very similar to those of real beef.	(Ge et al., 2025)

PPI = Pea Protein Isolate.

4.2. Structured lipid systems

The development of structured lipid systems is another key factor in reproducing the juiciness and thermal behavior of animal fat. Oleogels and multipolar emulsions enable controlled oil release during chewing and enhance sensory perception. The study by de Brito Sodré et al. (2025) showed that an açaí oil gel-emulsion with guar gum can reduce lipid oxidation, decrease cooking losses, modulate texture, improve the lipid profile, and maintain sensory acceptability up to 50 % fat replacement, demonstrating its potential as an alternative lipid system in plant-based meat substitutes. Lipids influence not only the final texture but also oxidative stability and matrix-lipid interaction, indicating the need for future research into kinetic oxidation modeling and integrated antioxidant strategies. In addition to their sensory benefits, these systems offer a lower-cost, more natural alternative to synthetic emulsifiers.

4.3. Improving flavor through fermentation, biocatalysis, and omics tools

Flavor remains the most complex challenge for meat analogues. Controlled fermentation with *Lactobacillus* and fungi has been shown to reduce vegetal and bitter notes, enhancing umami compounds and aromas characteristic of cured products (Martín-Miguélez et al., 2025; Razavizadeh et al., 2022), while specific enzymes such as proteases and lipases promote the formation of precursors of Maillard and Strecker reactions associated with more complex aroma profiles (Zhang et al., 2022). The integration of omic tools (metabolomics, volatilomics, and proteomics) with predictive artificial intelligence models offers new opportunities to map and predict the formation of aromatic compounds and to optimize formulations with greater precision and sensory consistency. For example, machine learning models can correlate volatilomic profiles with sensory data to identify specific combinations of

Table 6
Studies on meatballs.

Product type	Key finding	Sensory results	Reference
Fish meatballs with plant-based phenolic extracts from banana peel and cabbage	Polyphenol-rich extracts reduced peroxides and free fatty acids during storage.	Good color and flavor; acceptability preserved for up to 60 days when frozen.	(Ali et al., 2019)
Plant-based meatballs in sauce	A glossary of 14 sensory descriptors was developed to evaluate plant-based products objectively; the trained panel demonstrated good reproducibility and discriminatory ability.	The juiciness and "meaty" flavor of the new product improved compared to the commercial reference; appearance, firmness, and chewiness were similar to the control.	(Talens et al., 2024)
Vegetable meatballs made with young jackfruit	Cooking time affected physicochemical properties: increased browning index and water retention capacity with longer boiling times.	Boiled meatballs, cooked for 45 min, received the highest scores for appearance, flavor, and overall acceptability.	(Samutsri & Thimthuad, 2025)
Chicken-like meatballs made from protein concentrates from Indian legumes	Concentrated proteins (79 % and 87 %) showed differences in color and texture depending on the legume.	Treatment one (legume mixture) presented sensory characteristics closer to the chicken control in color, juiciness, and texture, with no significant differences ($p > 0.05$).	(Penchalaraju et al., 2025)

protein substrates, fermentation conditions, or enzymatic activities that maximize desirable attributes such as umami or reduce the generation of compounds responsible for undesirable flavors. These strategies make it possible to replace artificial flavorings, reducing the ultra-processed nature of plant-based meat substitutes.

4.4. Emerging protein sources

Alternative protein sources, such as microalgae, fungi, and cultured proteins, present opportunities to diversify technological functionality and improve the nutritional value of plant-based meat substitutes. Microalgae provide pigments and bioactive compounds, although they require mitigation of green notes, while fungi contribute natural fibers and umami (Ketnawa & Rawdkuen, 2023; Patinho et al., 2021). These sources reduce the use of additives due to their intrinsic techno-functional properties and, in some cases, offer competitive costs compared to traditional protein concentrates.

4.5. Sensory and consumer science

Traditional sensory methods conducted with trained panels do not always reflect the actual consumer experience, as the label "plant-based" can trigger cognitive biases and negative expectations that influence perceptions of taste, texture, and overall product acceptance. In this context, technological advances must align with sensory and consumer needs. Neuroscience-based studies have shown that implicit emotional responses to texture and aroma are decisive for acceptance, as they capture automatic reactions that are less influenced by prior beliefs or stigmas associated with meat substitutes (Grasso et al., 2022). Attachment to meat, perceptions of naturalness, and trust in ingredients critically influence purchase intention (Baune et al., 2023), while sustainable sensory communication strategies can modify expectations and willingness to pay (Caputo et al., 2023). In this regard, consumer neuroscience offers a key advantage by enabling sensory acceptance to be evaluated while minimizing bias induced by product information, thereby providing a more objective understanding of consumer responses. Integrating consumer neuroscience methodologies with sensory communication strategies will improve the alignment between expectations and sensory experience, increasing the likelihood of long-term adoption of these products.

In order to integrate the main challenges and opportunities identified, Fig. 10 presents a strategic roadmap for the next generation of plant-based meat analogues. This conceptual approach places consumer acceptance at the center and articulates three interdependent pillars: structure, flavor, and perception, which must be addressed in a coordinated manner to achieve technologically competitive and sensorially appealing products.

The future of the sector will depend on interdisciplinary approaches that combine engineering, biotechnology, sensory and consumer sciences, and social sciences, with a view to generating plant-based analogues that are technologically competitive, sensorially appealing, and culturally acceptable.

5. Conclusions

The bibliometric analysis carried out in this review reveals rapid growth in research on plant-based meat analogues from 2022 onwards, with a peak in publications in 2025, reflecting growing scientific interest in this field. It also identified prominent leadership from European countries, particularly Spain, along with strong contributions from Asian regions, and a thematic evolution from predominantly physicochemical approaches to more integrated research incorporating sensory evaluation and consumer-focused studies.

Plant-based meat analogues have emerged as a solid alternative to traditional meat, driven by demand for more sustainable, ethical, and healthier options. Recent studies demonstrate significant advances in formulation and processing, highlighting the use of soy, pea, and wheat proteins combined with structured oils and polysaccharides to improve texture, juiciness, and stability. Likewise, technologies such as high-moisture extrusion and controlled fermentation have enabled the production of more fibrous, cohesive structures, bringing plant-based products closer to the sensory properties of conventional meat.

However, significant challenges remain in replicating meat flavor, improving water retention, and optimizing the protein matrix, which are determining factors in consumer acceptance. Sensory fidelity, together with the perception of naturalness associated with "clean label" formulations, remains a limiting factor for the mass adoption of these products, as consumers demand alternatives that not only mimic the taste and texture of meat but also reduce the use of additives and functional agents perceived as artificial. In this context, the future success of plant-based products will depend on integrating technological innovation, nutritional development, and an understanding of consumer sensory and emotional behavior, thereby ensuring alternatives that combine pleasure, sustainability, and trust.

CRediT authorship contribution statement

Karina Eduardo: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Marianela Quispe:** Writing – review & editing, Conceptualization. **María Paz Velásquez:** Writing – review & editing. **Vanny Flores Enao:** Writing – review & editing. **Betsy Laura:** Writing – review & editing. **Yanett Villanueva:** Writing – review & editing. **Juan D. Rios-Mera:** Writing – review & editing, Conceptualization. **Erick Saldaña:** Writing – review & editing, Project administration, Conceptualization.

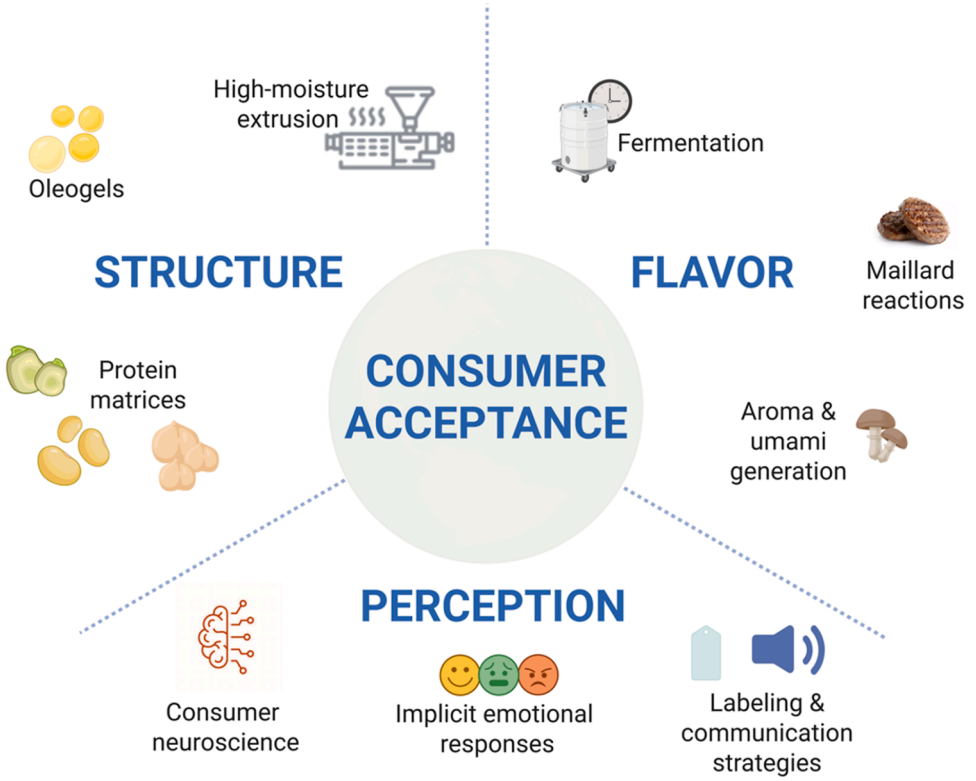


Fig. 10. Integrated approach for the next generation of plant-based meat analogues.

Declaration of competing interest

The authors have no conflict of interest in the manuscript "Plant-based meat substitutes: Trends, challenges, and opportunities from a bibliometric and systematic approach".

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.101884.

Data availability

Data will be made available on request.

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