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Sensory properties and consumer acceptance of plant-based meat, dairy, fish and eggs analogs: a systematic review

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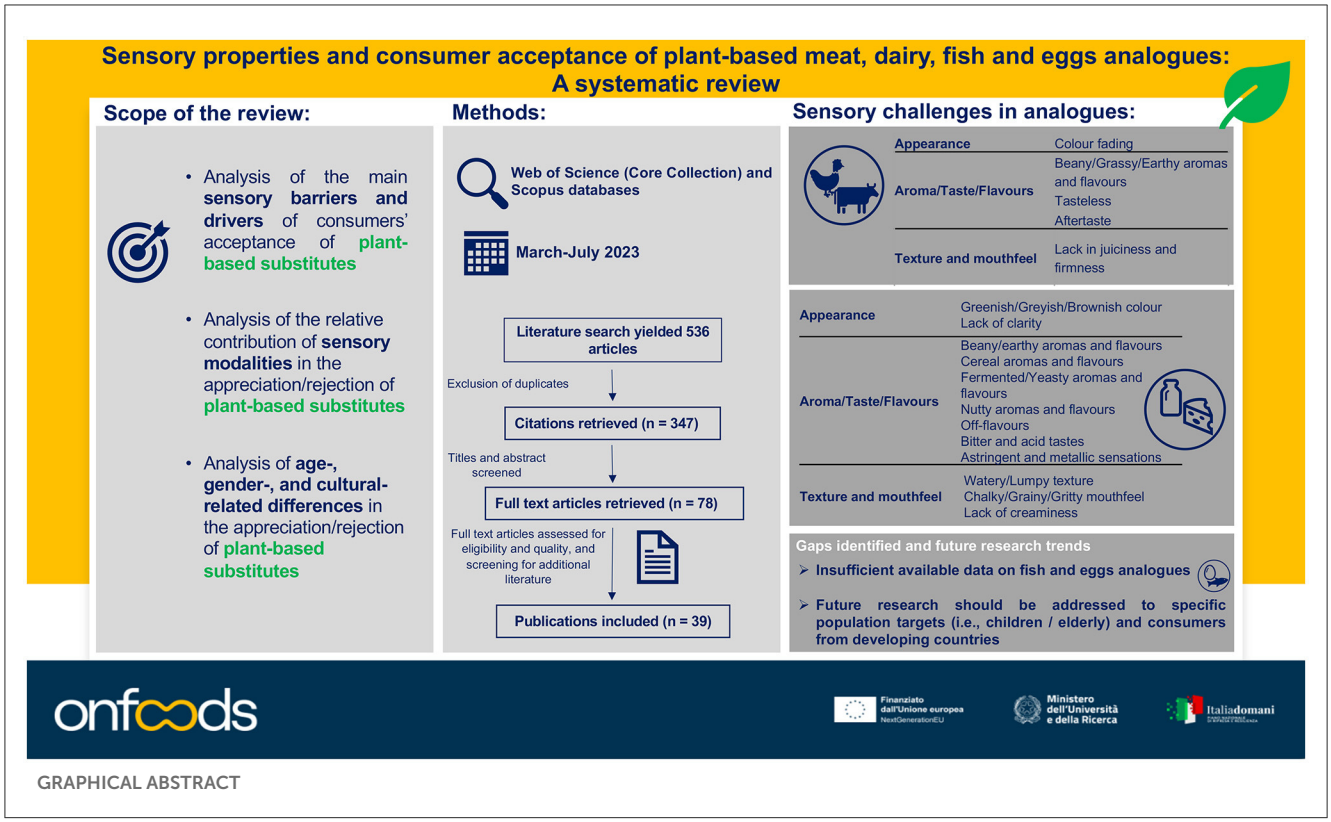
Introduction: Over the past years, several efforts have been made to formulate and develop plant-based substitutes of animal-based products in response to environmental changes, health issues and animal welfare. However, plant-based protein poses several challenges to product sensory characteristics, especially appearance, flavor, and texture. Despite this, current literature data have mainly reviewed nutritional, technological, and sustainability aspects of plant-based products with limited concerns on perceived sensory properties and perceptive barriers to consumption related to each specific substitute. To fill this literature gap, this systematic review aims to provide an up-to-date overview of the perceptive determinants of consumers' acceptance of plant-based substitutes of animal-origin products, including meat, dairy, fish and eggs analogs, with emphasis on product's intrinsic properties: appearance, smell, taste, and texture. Moreover, age-, gender-, and cultural-related differences in the appreciation/rejection of plant-based substitutes of animal-origin products were investigated.

Methods: The systematic analysis of the literature consulting Web of Science (Core Collection) and Scopus databases retrieved 13 research articles on meat, 26 on dairy, and two on fish and eggs analogs.

Results and discussion: Results showed that all sensory dimensions are influenced by the replacement of animal proteins with those of vegetable origin. However, the relative importance of appearance, odor, taste, and texture varied according to plant-based analogs category and mitigatory processing strategies to mask unpleasant sensory properties have been suggested for each category. Dairy analogs mainly suffer of aromas and flavors imparted by the raw materials, while both meat and dairy analogs have texture challenges. Meat analogs lack of juiciness, elasticity and firmness, while dairy analogs require uniform, creamy and thick texture. Moreover, very few studies analyzed the product's perception, considering age- and gender-related differences or cross-national/cultural differences. Future research should be addressed to specific product categories such as fish and eggs analogs as well as specific population targets including children and the elderly and consumers from developing countries.

KEYWORDS

alternative protein, plant-based protein, plant-based foods, liking, descriptive analysis, consumer research



GRAPHICAL ABSTRACT

1. Introduction

Nowadays, the food system is facing numerous challenges. Firstly, the demand for food is continuously growing due to the increase in the world population, which is expected to exceed 10 billion by 2050 (United Nations Department of Economic and Social Affairs, and Population Division, 2022). This ever-increasing demand for food clashes with the limited availability of resources, particularly land, water, and energy. In this context, food production could be considered one of the drivers of global environmental change contributing to climate emergency and biodiversity loss (Willett et al., 2019; Gibbs and Cappuccio, 2022). Moreover, today's dietary patterns, rich in meat and energy-rich foods and low in whole grains, fruit, and vegetables, are no longer sustainable and have severe consequences for human health (FAO, 2017).

In order to face these challenges and reduce the environmental impact that the food sector poses to climate change, a radical transformation of the food system should be performed by involving all stages, from food production to consumption. According to the FAO report on trends and challenges of the agri-food system, it is estimated that a 50% reduction in animal-based foods in the European Union would result in a 25%−40% reduction in greenhouse gas emissions associated with food production (FAO, 2017). One of the possible strategies for achieving this transition is the formulation of foods with alternative protein sources, such as edible insects, algae, or pulses.

Plant-based food formulated as a substitute for animal-based products is one of the growing sectors among alternative food sources, encompassing a diverse range of products obtained from botanical sources, such as legumes (e.g., soy, lupine, chickpea, pea), seeds and nuts (e.g., cottonseed, sesame seed, sunflower seed, pumpkin seed, grape seed, hazelnut), pseudocereals and cereals (e.g., quinoa, oat), and mushrooms (Tachie et al., 2023). They are developed to mimic the appearance, taste, texture, and sensory characteristics of their conventional animal counterparts, such as meat, milk, fish and eggs (McClements and Grossmann, 2021a). This type of food represents a valuable opportunity for consumers who want to decrease the environmental impact of their food choices by limiting (e.g., flexitarians) or avoiding partially (e.g., vegetarians) or totally (e.g., vegans) the consumption of animal products (Smart Protein Project, 2021; Bryant, 2022).

According to Life Cycle Assessment (LCA) studies, plant-based foods are more environmentally sustainable regarding greenhouse gas emissions, land use, water use, and energy use (Smetana et al., 2021; Bryant, 2022). In addition, these foods are reported to have health benefits contributing to a decrease in the risk of cardiovascular disease (Jafari et al., 2021), being lower in fat and cholesterol and higher in fiber compared to their animal-origin counterpart (Nolden and Forde, 2023). However, their health long-term impact is still uncertain (Tso and Forde, 2021).

1.1. Plant-based food substitutes market

In recent years, at the global level, the market of plant-based alternatives has experienced significant growth, reaching $28 billion in 2022 in total retail sales (Euromonitor data, 2023) and it is expected to reach $77.8 billion in 2025 (Statista, 2023). While in Europe, it was valued at €5.7 billion in 2022, representing a growth of 22% compared to 2020 (The Good Food Institute Europe, 2022). The plant-based food market success is driven mainly by flexitarian consumers, the most important target group for these products accounting for 30% of Europeans, while vegetarians and vegans correspond to 7% (Smart Protein Project, 2021).

Today, plant-based food sector includes plant-based meat analogs (i.e., sausages, chicken, burgers, nuggets, tenders, and cutlets), dairy alternatives (e.g., yogurt, cheese, milk), egg substitutes (e.g., mayonnaise) and plant-based seafood (e.g., slices, filets, fish sticks, and fish burgers) (Alcorta et al., 2021; Lima et al., 2022). The global plant-based meat market hit $5.3 billion in 2021 and is expected to reach $33.3 billion by 2031, with a 20.5% Compound Annual Growth Rate (CAGR) from 2022 to 2031 (Allied Market Research, 2022a), while plant-based dairy products were valued at $11.2 billion in 2021, and estimates anticipate a climb to $31.5 billion by 2028, driven by a 10.5% CAGR between 2022 and 2028 (Facts and Factors Research, 2022). Instead, the global plant-based seafood market size was valued at $42.1 million in 2021, and is projected to reach $1.3 billion by 2031, growing at a CAGR of 42.3% from 2022 to 2031 (Allied Market Research, 2022b).

Considering the European scenario, the leading categories are plant-based milk and meat (Smart Protein Project, 2021), which account for 38 and 35% of total plant-based food sales, respectively (The Good Food Institute Europe, 2022). Both sectors are led by Germany, which is Europe's largest plant-based food retail market (The Good Food Institute Europe, 2022). The German plant-based meat sales were €642.8 million in 2022, followed by United Kingdom (UK; €530 million) and the Netherlands (€221 million). Germany recorded €552 million in sales for plant-based milk, followed by Spain (€353 million) and Italy (€310 million). Interestingly, these two categories outpaced animal-based categories in unit sales growth (The Good Food Institute Europe, 2022). Concerning plant-based fish, although this sector is still at an early stage of development and its offer is still limited, the value of its sales recorded in Europe one of the fastest growth rates (326%) between 2020 and 2022, especially in Spain (6,430%), Austria (1,327%), Germany (310%), and Belgium (37%) (The Good Food Institute Europe, 2022).

1.2. Overview of the main drivers and barriers to the consumption of plant-based substitutes

Taken together, these retail data market show that the interest of consumers in animal-based substitutes has increased significantly. Nevertheless, the plant-based food market remains a niche market, probably because various challenges hinder its success (Alcorta et al., 2021; Lima et al., 2022). The barriers to the consumption of plant-based substitutes of animal-origin products are both person-related factors such as socio-demographics, dietary status, psychological and physiological variables as well as product-related factors (Giacalone et al., 2022), including food convenience (e.g., price, preparation time, food availability), credence attributes (e.g., healthiness, naturalness, sustainability and animal welfare), and sensory properties (appearance, taste, flavor, and texture) (Tuorila and Hartmann, 2020; Giacalone et al., 2022).

In a recent review by Eckl et al. (2021), and several related articles (Banovic and Sveinsdóttir, 2021; Davitt et al., 2021; Michel et al., 2021; Sijtsema et al., 2021; Pointke et al., 2022), the barriers and facilitators underlying replacing meat with plant-based protein sources in omnivores and flexitarians were identified examining personal, sociocultural, and external factors. The desire to reduce meat consumption—mainly driven by environmental issues and animal welfare—the use of packaging and labels displaying claims, such as "vegan," "environmentally friendly," or "lighter footprint," might act as stimuli to replace meat with alternative protein sources, especially in women. On the contrary, being male, showing a greater meat attachment, presenting higher food neophobia attitudes, rating low the situational appropriateness of consuming plant-based meat alternatives, and the high price of these products may act as inhibitors.

Another essential point in the context of plant-based food alternatives is the "health issue." A recent review about the nutritional quality of plant-based products (Nolden and Forde, 2023), compared the nutritional composition, in terms of macro- and micronutrients, of these alternatives to their conventional animal counterparts. The authors highlighted many differences in nutrient composition and bioavailability between plant- and animal-based products, with the former generally being nutritionally inferior to their animal counterparts. It should be underlined that there is much confusion, especially in the mind of the consumer, regarding the quality of analogs of products of animal origin. It has been reported that some consumers consider the consumption of plant-based substitutes to be beneficial because these products contain a high protein content and low amount of total and saturated fat in the case of plant-based meat (Pointke et al., 2022), while plant-based milks have reduced caloric content and are lactose-free (Aydar et al., 2020). However, these products are also perceived as unhealthy, ultra-processed and artificial, and their nutritional value is often unclear. This paradox in the mind of consumers could lie in the fact that meat, milk, fish and eggs analogs are meant to replicate products, which are perceived as a single food component, whereas plant-based analogs are formulated by using multiple food ingredients, at times unfamiliar (Elzerman et al., 2013; Kerslake et al., 2022; Pointke et al., 2022; Martínez-Padilla et al., 2023). The use of multiple ingredients, flavors and additives in these foods has a significant impact on their technological, nutritional and, especially, sensory properties (i.e., texture, taste and appearance), which are fundamental aspects that let or not consumers choose plant-based substitutes over animal origin food (Short et al., 2021; Smart Protein Project, 2021).

Among all the barriers and drivers, sensory properties certainly have a fundamental role in the acceptability of plant-based substitutes for animal-origin products. Plant-based protein poses several challenges to the sensory characteristics of the product, especially appearance, taste, and texture (Tso et al., 2020; Kerslake

et al., 2022), also considering that these products are designed to recreate the sensory experience of animal-based foods, which are also sometimes referred to in slogans such as "tastes like meat" on the packaging. This generates clear expectations that are often not fulfilled, especially among the flexitarian consumer who still consumes traditional animal-based foods (Cardello et al., 2022; Tachie et al., 2023).

To foster the development of plant-based substitutes, their sensory characteristics should be optimized to mimic those of the original animal version. In this context, sensory studies and consumer science provide valuable support in understanding how consumers perceive food and which sensory attributes should be modulated to increase acceptance (Aschemann-Witzel et al., 2019; Palczak et al., 2019).

1.3. Objective of the review

Despite the clear importance of plant-based products' sensory quality optimisation, until now, literature reviews have mainly focused on nutritional, technological and sustainability aspects by analyzing plant-based alternatives (McClements and Grossmann, 2021a,b; Lima et al., 2022; Sridhar et al., 2022) or focusing on a single product type, such as plant-based dairy (McClements et al., 2019; Silva et al., 2020; Bocker and Silva, 2022; Craig et al., 2022), plant-based meat (Singh et al., 2021; Ishaq et al., 2022; Tyndall et al., 2022; Andreani et al., 2023) and plant-based seafood analogs (Kazir and Livney, 2021; Nowacka et al., 2023).

By contrast, to the best of our knowledge, limited concerns about perceived sensory properties and perceptive barriers related to each specific substitute have gained attention in the literature review, and even in these cases, the attention was only directed to plant-based meat (Fiorentini et al., 2020; Starowicz et al., 2022), plant-based cheese (Short et al., 2021) or to plant-based meat and cheese analogs but focusing only on texture properties (Moss et al., 2023). The only brief review article examining consumer perceptive barriers was Giacalone et al. (2022), which only focused on meat and dairy products. To fill this literature gap, this systematic review aims to provide an up-to-date overview of the sensory determinants of consumers' acceptance of plant-based substitutes of animal-origin products, including meat, dairy, fish and eggs analogs (also referred to as meat, dairy, fish and eggs substitutes or alternatives), with emphasis on product's intrinsic properties, i.e., appearance, smell, taste, and texture. Plant-based meat and milk will be covered in two separate sections, while eggs and fish substitutes will be discussed together as there is still limited research on them. Moreover, possible perceptive differences will be analyzed in population targets varying in age, gender and cultural background.

The specific research questions to which the present systematic review aims to answer are:

1. What is the most recent and available information about the main sensory barriers and drivers of consumers' acceptance of plant-based substitutes of animal-origin products?
2. What is the relative contribution of appearance, smell, taste, and texture in the appreciation/rejection of plant-based substitutes of animal-origin products? Are there product-related differences in sensory determinants of appreciation/rejection?
3. Are there age-, gender-, and cultural-related differences in the appreciation/rejection of plant-based substitutes of animal-origin products?

This systematic literature review will record data on an aggregate level, and no meta-analysis was planned due to the expected heterogeneity in study design, participant recruitment, outcome, and measurements.

The results of this review are reported first by providing an overview of the studies' characteristics and then by reviewing the outcomes on hedonistic and perceptual determinants with emphasis on specific population targets. The results of this review are expected to provide valuable insights for the food industry in order to develop plant-based meat, dairy, fish and egg analogs which are optimized from a sensory point of view and are well-accepted by consumers, thus encouraging their consumption within a sustainable diet.

2. Method

2.1. Search strategy

The literature search was conducted between March and July 2023 consulting Web of Science (Core Collection) and Scopus databases. The following search string was used: (*"sensory profil" OR "descriptive analysis" OR "sensory perception" OR "characterisation" OR "characterization" OR "food choice" OR "food accept*" OR "food liking" OR "food adoption" OR "food appreciation" OR "food rejection" OR "food disliking"*) AND (*"Plant-based food*" OR "Plant-based meat" OR "Plant-based milk" OR "Plant-based yoghurt" OR "Plant-based egg*" OR "Plant-based fish" OR "Plant-based dairy" OR "Plant-based cheese*" OR "meat-analogue*" OR "milk-analogue*" OR "yoghurt-analogue*" OR "egg-analogue*" OR "fish-analogue*" OR "dairy-analogue*" OR "cheese-analogue*" OR "meat alternative*" OR "milk alternative*" OR "yoghurt alternative*" OR "egg alternative*" OR "fish alternative*" OR "dairy alternative*" OR "cheese alternative*" OR "meat substitute*" OR "milk substitute*" OR "yoghurt substitute*" OR "egg substitute*" OR "fish substitute*" OR "dairy substitute*" OR "cheese substitute*"*).

The last literature search was done on July 5th, 2023 by entering within the "Article title, abstract, keywords" section of both databases the two batteries of keywords. No temporal restriction has been applied to the search of published literature.

2.2. Articles selection

A flow chart summarizing the study selection process is depicted in Figure 1. Two independent researchers conducted the literature search and checked if there were duplicates. A total of 536 articles were returned by Scopus ($n = 296$) and Web of Science ($n = 240$). After excluding duplicates ($n = 189$), the remaining 347 articles were screened against inclusion and exclusion criteria (Table 1). First, articles were screened based on titles and abstracts by two independent researchers. Any disagreement between the

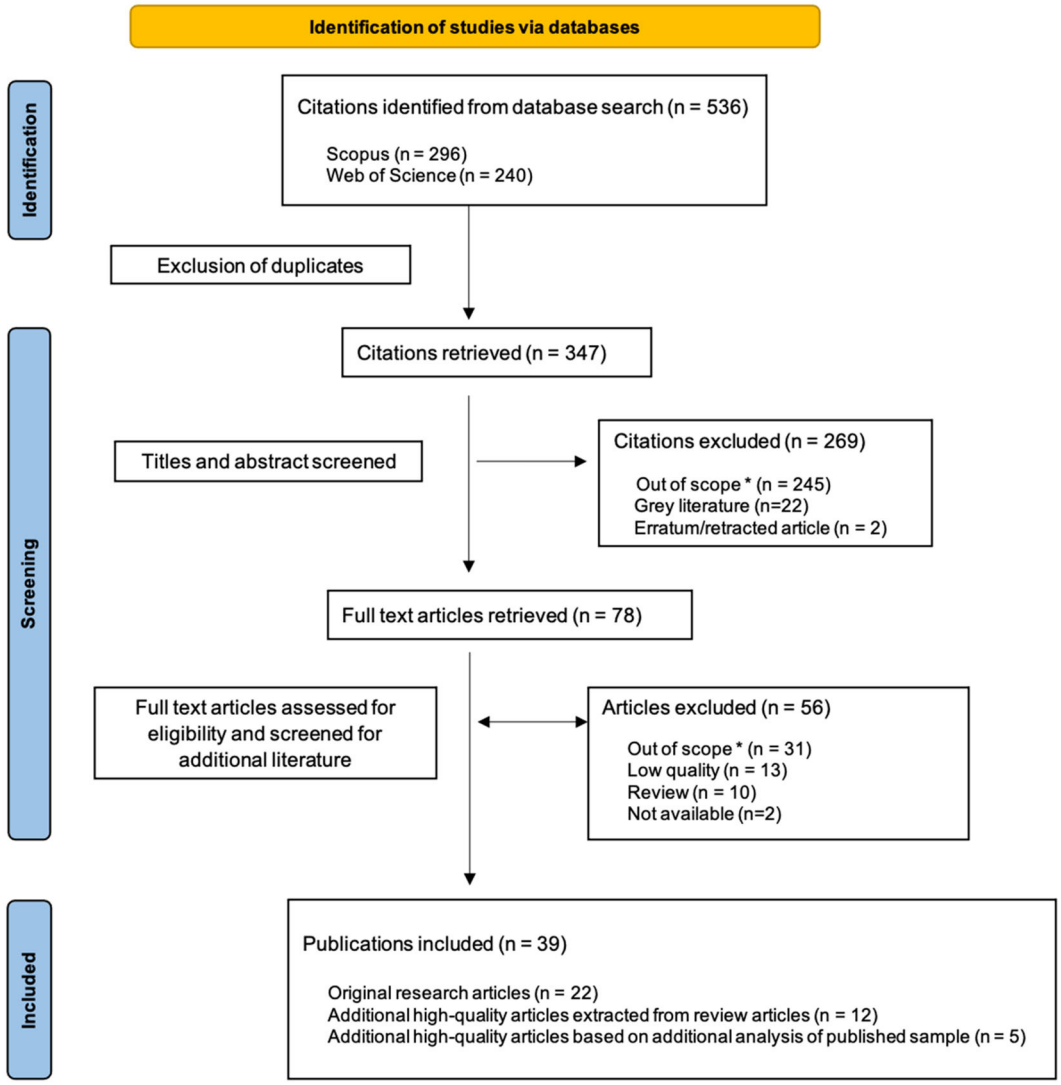


FIGURE 1
Flow chart of the different phases of the systematic review (Page et al., 2021). *Articles removed because "out of scope" include both studies dealing only with nutritional and/or instrumental data and studies addressing alternative protein in general without focusing on analogs of animal origin food products.

two researchers was solved by discussion or with the help of a third researcher when necessary. In case of persisting doubts about eligibility, articles were kept for the following step. Overall, 269 articles were excluded because they did not meet the inclusion criteria. The resulting eligible articles for full-text screening were 78. This phase was performed by two independent reviewers and was associated with data extraction of those articles that were considered eligible based on inclusion and exclusion criteria (Table 1) and quality assessment (see section 2.4. for details). Any disagreement between the two reviewers was solved by discussion or with the help of a third reviewer when necessary. Review articles were excluded from the systematic review but were analyzed to search for additional eligible articles likewise screened for quality assessment ($n = 10$). The resulting eligible articles used in the present systematic review are 39, obtained from original research articles ($n = 22$), and additional papers extracted from reviews ($n = 12$) or further analysis of the screened research articles ($n = 5$; Figure 1). The same selection process, screening for eligibility criteria and quality assessment have been applied to these additional papers.

2.3. Data extraction process

Data extraction included general citation information (title, authors, year of publication, doi link, database), study characteristics (year of data collection, abstract, objective of the study, sample size, study design/methodological approach), participants' characteristics (age, gender, country, socio-economic status, dietary habits), determinants of liking/acceptance of novel food explored (psychological traits, individual biological

TABLE 1 Inclusion and exclusion criteria used for article selection.

Item	Inclusion criteria	Exclusion criteria
Participants/ population	Studies conducted on individuals of any age and	Studies with participants acutely ill or with specific disease
	from any country	Studies performed in the hospitals or nursing home setting
Outcome	Both quantitative and qualitative outcomes;	Studies dealing only with nutritional and/or instrumental data
	Studies dealing with acceptance and/or descriptive data about analogs of animal origin food products	Studies addressing alternative protein in general without focusing on analogs of animal origin food products
Study design	No restriction on study design	Review articles (considered only for additional articles inclusion)
Articles characteristics	Peer-reviewed journal papers; No publication date restriction; Studies published in English	Gray literature (e.g., thesis, book chapters, reports and conference abstracts)

factors, attitudes toward food), outcome (data type, e.g. hedonic, descriptive), findings (type of product/ingredient, main results, conclusion/final remarks). The summary of the main information extracted from eligible articles is shown in Tables 2–4.

2.4. Articles quality assessment

A quality assessment of each article ($n = 78$) was performed during the phases of full-text screening against inclusion and exclusion criteria and data extraction following the procedure suggested by Kmet et al. (2004). The checklist for articles' quality assessment comprised all the 14 criteria proposed by Kmet et al. (2004):

1. *Question/objective sufficiently described?*
2. *Study design evident and appropriate?*
3. *Method of subject selection is described and appropriate?*
4. *Subject characteristics are sufficiently described?*
5. *If interventional and random allocation was possible, is it described?*
6. *If interventional and blinding of investigators was possible, is it described?*
7. *If interventional and blinding of subjects was possible, is it reported?*
8. *Outcome measures(s) well defined and robust to measurement/misclassification bias? Means of assessment reported?*
9. *Sample size appropriate?*
10. *Analytic methods described/justified and appropriate?*
11. *Some estimate of variance is reported for main results?*
12. *Controlled for confounding?*
13. *Results reported in sufficient detail?*
14. *Conclusions supported by results?*

Each question can be answered with "yes," "partial," "no," and "not applicable." A summary score was calculated for each article as follows:

$$\begin{aligned} Total\ sum &= (number\ of\ \text{“}yes\text{”} \times 2) \\ &+ (number\ of\ \text{“}partial\text{”} \times 1) \quad (1) \\ Total\ possible\ sum &= 28 \\ &- (number\ of\ \text{“}not\ applicable\text{”} \times 2) \quad (2) \\ Summary\ score &= \frac{Total\ sum}{Total\ possible\ sum}. \quad (3) \end{aligned}$$

The manual for quality scoring of qualitative and quantitative studies provided by Kmet et al. (2004) guided the scoring process. Two independent reviewers evaluated each article. An average score was calculated between the two reviewers' scores for each article. All articles reaching an average quality score ≥ 0.70 were included in the final report. In other words, inclusion was firstly based on compliance with the inclusion criteria, and secondly on achieving a threshold quality score. Conflicting judgments regarding the inclusion of articles were resolved through discussion between the reviewers.

The resulting eligible articles in the present report are 39 (Figure 1). Further information about all articles is available in Supplementary files.

3. Results

3.1. Meat analogs

3.1.1. Studies' characteristics

An overview of the characteristics of the 13 studies on meat analogs included in this review is provided in Table 2. The studies were published from 2008 to 2022 and focused on different plant-based meat analogs, such as burgers patties or chicken pieces (Piester et al., 2020; Godschalk-Broers et al., 2022; Kerslake et al., 2022; Pater et al., 2022), cold cuts (Pointke et al., 2022), and samples or recipes with legume-based or fungi-based analogs (Katayama and Wilson, 2008; Elzerman et al., 2013; Hoek et al., 2013; Gómez et al., 2019; Cordelle et al., 2022).

The majority ($n = 10$) were conducted in Europe (Hoek et al., 2011, 2013; Elzerman et al., 2013; Gómez et al., 2019; Grasso et al., 2021; Michel et al., 2021; Cordelle et al., 2022; Godschalk-Broers et al., 2022; Pater et al., 2022; Pointke et al., 2022). Two research articles were conducted in the United States (US) (Katayama and Wilson, 2008; Piester et al., 2020) and one in New Zealand (Kerslake et al., 2022). Notably, two studies were cross-national and involved consumers from The Netherlands and the UK (Hoek et al., 2011) and from Finland, Poland, Spain, the Netherlands, and the UK (Grasso et al., 2021). To note, none of the studies involved participants from Africa, Asia, or Latin America.

As regard the target population, the majority ($n = 11$) focused on the adult population (over 18 y.o.), one study specifically focused on older people (Grasso et al., 2021), and one on children (Pater et al., 2022).

Three studies applied a qualitative approach using either focus groups (Elzerman et al., 2013; Kerslake et al., 2022) or semi-structured interviews (Pater et al., 2022). All other studies ($n =$

TABLE 2 Characteristics of the studies on plant-based meat analogs (M, males; F, females; O, others; PB, plant-based; N/A, not available).

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
Kerslake et al. (2022)	New Zeland	35 (M 31%; F 69%) Age range: N/A Food habits: Omnivorous 34%; Vegetarian 34%; Vegan 32%	Qualitative	Focus group	PB meat analogs
Pater et al. (2022)	The Netherlands	34 (M 47%; F 53%) Age range: 8–10 years Food habits: Non-vegetarian	Qualitative	One-to-one interviews	2 PB commercial samples: burgers and balls
Elzerman et al. (2013)	The Netherlands	45 (M 25%; F 75%) Age range: 20–60 years Food habits: Non-vegetarian	Qualitative	Focus group	2 PB mince (tofu and Quorn) in pasta sauce
Pointke et al. (2022)	Germany	159 (M 30%; F 70%) Age range: 18–70 years Food habits: Omnivorous 22%; Flexitarian 39%; Vegetarian 28%; Vegan 11%	Quantitative	- Questionnaires on behavioral attitudes - RATA - Overall liking	1 PB salami
Godschalk-Broers et al. (2022)	The Netherlands	71 (M 37%; F 63%) Age range: 19–41 years Food habits: Non-vegetarian	Quantitative	- Descriptive (method not specified) - Overall liking	14 commercial chicken pieces: 1 real chicken pieces and 13 PB chicken pieces analogs; 15 commercial burger patties: 1 beef burger patty and 14 PB burger patties analogs
Gómez et al. (2019)	Spain	73 (M 56%; F 44%) Age range: 18–65 years	Quantitative	- Liking for color (intensity, homogeneity) and odor (intensity, persistence, cooked meat) + overall liking	4 commercial samples after *sous vide* cooking: 2 beef samples (teriyaki and beer marinades, cooked at 70°C for 90 min) and 2 meat analogs (teriyaki and beer marinades, cooked at 70°C for 120 min)
Grasso et al. (2021)	Finland, Poland, Spain, the Netherlands, the UK	2,478 (M 52%; F 48%) - Age range: 65–75 years - Country: Finland 19.9%; Poland 20.1%; Spain 20.2%; The Netherlands 20.1%; UK 19.7%	Quantitative	Questionnaires on behavioral attitudes	N/A
Michel et al. (2021)	Germany	1,039 (M 49%; F 51%) Age range: 20–69 years Food habits: Omnivorous 74%; Pescatarian 2%; Flexitarian 20%; Vegetarian 3%; Vegan 1.5%	Quantitative	Questionnaires on behavioral attitudes	N/A
Cordelle et al. (2022)	France	91 (M 51%; F 49%) Age range: 18–65 years	Quantitative	- CATA (descriptive) - Overall liking	White Sauce, Chop Suey and Lasagna recipes prepared either with PB protein chunks (soy or a mix of wheat and chickpea) or with meat chunks (veal, chicken or ham)
		68 (M 52%; F 48%) Age range: 20–65 years	Quantitative	- Multiple-intake temporal dominance of sensations (TDS) - Visual liking before tasting - Appearance liking before tasting - Liking for taste and texture	White Sauce recipe prepared with chicken chunks or three different plant-based protein chunks (Wheat-Soy, Mycoprotein and wheat and chickpea)
Katayama and Wilson (2008)	USA	14 (no info about gender and age range)	Quantitative	Descriptive (sensory profile)	Textured soy protein samples with vegetable chicken or shrimp flavors (0%—22.3% concentrations) with different extruded-shapes (narrow die, wider die, shred-shaped strips, and 1-cm crouton-shaped bits)
		125 (M 30%; F 68%; O 2%) Age range: 18–64 years	Quantitative	- Overall liking - Choice of preferred product	4 Textured soy protein samples with vegetable chicken flavors (22.3%) baked or fried

(Continued)

TABLE 2 (Continued)

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
Hoek et al. (2011)	The UK and The Netherlands	553 (M 35%; F 65%) Age range N/A Country: UK 43%; The Netherlands 57%; - Type of diet: vegetarian 50%	Quantitative	Questionnaires on behavioral attitudes	N/A
Hoek et al. (2013)	The Netherlands	89 (M 35%; F 65%) Age range: 18–66 Type of diet: Non-vegetarian	Quantitative	- Questionnaires on behavioral attitudes - Overall liking over exposures	3 hot meal recipes with Quorn, Tofu and chicken filet
Piester et al. (2020)	USA	228 (M 49%; F 51%) Age range: over 18 years	Quantitative	Questionnaires on behavioral attitudes	N/A
		303 (M 35%; F 63%; O 2%) Age range: over 18 years	Quantitative	Overall liking	PB burger

10) employed quantitative research methods, with three exclusively using surveys (Hoek et al., 2011; Grasso et al., 2021; Michel et al., 2021), and seven studies utilizing an experimental design (hedonic method: Hoek et al., 2013; Gómez et al., 2019; Piester et al., 2020; descriptive and hedonic methods: Katayama and Wilson, 2008; Cordelle et al., 2022; Godschalk-Broers et al., 2022; Pointke et al., 2022).

3.1.2. Analysis of the hedonic and perceptive determinants of plant-based meat analogs

Since most of the studies focused on a very wide range of products that did not allow a simple categorization by type of product (e.g., chicken, burgers etc), meat analogs are reported in a single paragraph.

Over the past years, several efforts have been made to develop alternative products to real meat (e.g., plant-based meat analogs, edible insects, and cultured meat) (Lee et al., 2020). Among them, plant-based meat analogs are food products that mimic the aesthetic qualities, sensory and chemical characteristics of certain types of meat, replacing meat proteins with vegetable proteins such as textured soy protein, mycoproteins, wheat gluten, and pulses (Joshi and Kumar, 2015; Bohrer, 2019) using extrusion, spinning, and simple shear flow production techniques (Bohrer, 2019).

It is well-known that sensory characteristics strongly influence which products individuals choose to consume, and this is particularly important when considering plant- or fungi-based products as alternatives to meat (Hartmann and Siegrist, 2017; Siegrist and Hartmann, 2019). In a recent brief review, Giacalone et al. (2022) highlighted that the sensory quality of plant-based meat alternatives remains disappointing, and they performed worse in sensory evaluations when compared to the meat-control product. Accordingly, some studies examined in the present review reported that meat substitutes are poorly rated, lack sufficient quality in terms of flavor and texture (firmness, juiciness, greasiness), and present unpleasant aftertastes (Hoek et al., 2011; Elzerman et al., 2013; Michel et al., 2021; Kerslake et al., 2022). However, the debate on which characteristics should be present in meat analogs is still ongoing since some consumers prefer properties that mimic real meat properties (Hoek et al., 2011; Michel et al., 2021; Cordelle et al., 2022; Pater et al., 2022), and others would like flavors and textures that do not resemble meat. This latter group of consumers would like to refer to meat analogs as products with unique characteristics and not anymore as "analogs/substitutes" (Elzerman et al., 2013; Kerslake et al., 2022).

In general, in the critical moment when a consumer approaches a food, perhaps for the first time, a disconfirmation of expectations occurs if the score of perceived liking after consumption is lower than the score of expected liking, meaning that the product's appearance misrepresents other characteristics like odor, taste, and flavor (Delwiche, 2004). Firstly, the overall appearance of meat analogs should inspire positive expectations that are also confirmed during consumption (Fiorentini et al., 2020). However, using plant proteins is associated with processing limitations, such as color fading when the analog is exposed to light or oxygen, resulting in an unattractive product (Fiorentini et al., 2020). Thus, several approaches, like seasoning and curing the meat analogs before cooking, as well as cooking parameters such as temperature and time, could be applied to impact the visual appearance of meat analogs positively. Gómez et al. (2019) examined the effect of two marinades (i.e., teriyaki sauce and beer) and different cooking times and temperatures on the color attributes of a soy meat analog and a beef equivalent. Both ready-to-eat products were subjected to *sous vide* cooking (i.e., a vacuum-sealed product is cooked at low temperatures in a water bath) at different combinations of temperature (70°C and 80°C) and time (60, 90 and 120 min for beef; 90, 120 and 150 min for meat analog) (Gómez et al., 2019). The use of teriyaki sauce (70% of pineapple juice) and pale lager beer (80%) as marinades, resulted in a light-yellow or golden color, respectively. Seventy-three consumers performed, in a blind condition, a hedonic test on color (intensity, homogeneity, and overall color), and odor (intensity, persistence, cooked meat, and overall odor) parameters using a 7-point scale (1 = "dislike very much," 7 = "like very much"). Regarding appearance, hedonic scores were found comparable between the samples (around the mid-point of the scale "neither liked nor disliked"), suggesting that both samples were equally liked in terms of visual appearance. In addition, lightness and redness parameters evaluated with the instrumental analysis had the same values in both samples cooked with

TABLE 3 Characteristics of the studies on plant-based dairy analogs (M, males; F, females; PB, plant-based; N/A, not available).

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
Laaksonen et al. (2021)	Finland	14 (M 50%; F 50%) Age range: N/A	Quantitative	Descriptive (sensory profile)	6 Lupine beverages (1 sample unfermented and 5 fermented for one day)
		22 (M 41%; F 59%) Age range: 21–61 years	Quantitative	- Pleasantness of color, appearance, odor, flavor and overall liking - 5-point Just About Right scale for bitterness, sweetness, sourness, astringency	8 Lupine beverages (2 sample unfermented with and without thickening agents and 3 fermented for one day with and without thickening agents)
Mefleh et al. (2022)	Italy	13 (M 54%; F 46%) Age range: 25–52 years	Quantitative	Descriptive (quantitative descriptive analysis)	4 legume-based beverages from an Apulian black chickpeas protein concentrate (1 sample not inoculated and 3 fermented with three starter cultures)
Cosson et al. (2020)	France	16 (M 6%; F 94%) Age range: 18–39 years	Quantitative	- Descriptive (static block profile) - Mono-intake temporal dominance of sensations (TDS) profiling - Multi-intake TDS profiling	12 pea protein-based beverages varying in pea protein type (pellet vs. isolate) and content of gellan gum, salt, sunflower oil, sugar, and soy lecithin
Aydar et al. (2023)	Turkey	11 (gender N/A) Age range: 22–50 years	Quantitative	- Descriptive (Sensory Profile) - Overall liking	3 Kidney bean beverages (one commercial sample + oval kidney bean milk sample + cherry kidney bean milk sample)
Chung et al. (2022)	Taiwan	9 (M 33%; F 67%) Age range: 20–65 years	Quantitative	Descriptive (quantitative descriptive analysis)	12 commercial samples: 1 cow milk and 11 PB milk analogs (6 oat, 2 soy, 2 coconut and 1 almond)
		- 80 (M 36%; F 64%) - Age range: 20–65 years	Quantitative	- CATA (descriptive) + ideal - Overall liking	
Cardello et al. (2022)	New Zealand	345 (M 46%; F 54%) Age range: 20–66 years Ethnicity: New Zealand European 65%; Maori 10% - Pacific Island 6%; Australian 1%; European 5%; North American 1%; Chinese 8%; Indian 11%; Southeast Asian 5%; others 6%	Quantitative	- CATA (descriptive) - Overall liking - CATA for emotional/cognitive perceptions, and situational uses	10 commercial samples: 2 cow milk samples (3.4% and 0.1% fat content levels), 1 lactose-free cow milk sample (3.4% fat), 2 sweetened soy milk samples (3.0% and 1.4% fat content levels), 2 cashew nut milk (sweetened and unsweetened), 1 rice milk (unsweetened), 1 oat milk (unsweetened), and 1 blend sample from three PB ingredients: oat, rice, and coconut
Oduro et al. (2021)	Ghana	180 (gender N/A) Age range: 17–54 years	Quantitative	T-Map scale version of relative preference mapping	8 samples: 2 commercial samples (soymilk and sweetened UHT milk) + 6 prototypes of 3-blend PB milk alternatives (Coconut, Peanut, Tiger nut, Melon seeds)
Pramudya et al. (2019)	USA	10 (Gender N/A) - Age range: N/A	Quantitative	Descriptive (Sensory Profile)	7 commercial rice-based milk analog samples varying in amounts of sugar and sodium, rice milling degree (milled, partially milled, or brown rice), flavor additives, and micronutrient fortification
		101 (M 39%; F 61%) Age range: 19–74 years Ethnicity: Caucasians 79.2%; Asians 9.8%; Latinos 4.0%; African-Americans 2.0%; Native Americans 1.0%; Others 4.0%	Quantitative	- Overall liking - Food neophobia	

(Continued)

TABLE 3 (Continued)

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
Vaikma et al. (2021)	Estonia	10 (M 10%; F 90%) Age range: 24–41 years	Quantitative	RATA	90 commercial PB analog samples: 26 almond, 25 oat, 14 soy, 11 rice, 6 coconut, 2 hazelnut, 2 cashew, 2 buckwheat, 1 hemp, 1 brazil nut, 1 quinoa
Lawrence et al. (2015)	USA	8 (F 100%) Age range: 22–45 years	Quantitative	Descriptive (sensory profile)	26 commercial unflavoured soymilks
		235 (F 100%) Age range: 18–64 years - Ethnicity: Caucasian/African Americans; Asians	Quantitative	- Appearance, color and aroma liking before tasting - Liking for flavor, sweetness, thickness, aftertaste + overall liking - 5-point Just About Right scale for color, flavor, sweetness, thickness	12 commercial unflavoured soymilks
Chambers et al. (2006)	USA	5 (gender: N/A) Age range: N/A	Quantitative	Descriptive (flavor profile)	32 commercial unflavoured soymilks
N'Kouka et al. (2006)	USA	9 (M 22%; F 78%) Age range: 24–32 years	Quantitative	Descriptive (sensory profile)	6 soymilk samples: 5 commercial samples + 1 prototype
Jaeger and Giacalone (2021)	USA	603 (M 50%; F 50%) Age range: 18–65 years Ethnicity: White/Caucasian 86%; Black/African American 5%; Spanish/Hispanic/Latino 6%; Asian 5%; Native American 1%; Others 1%	Quantitative	- Overall liking - CATA for emotional/conceptual/situational/attitudinal perceptions, and situational uses - Food neophobia	3 samples' pairs: Cow's milk vs. Oat milk, Fruit smoothie vs. Fruit smoothie with soy milk, Iced coffee vs. Iced coffee with almond milk
Palacios et al. (2010)	USA	425 (gender: N/A) Age range: 8–16 years Ethnicity: Caucasian 52.2%; African American 24.5%; Asian 23.3%;	Quantitative	- Liking for overall appearance, taste, smell - Liking for color, sweetness, mouthfeel, aftertaste + overall liking	3 lactose-free unflavoured cow's milk products with different fat content levels (2%, 1% and fat-free), 1 unflavoured soymilk at 1% fat level sample, 1 chocolate lactose-free cow's milk at 1% fat level sample, and 1 chocolate soymilk at 1% fat level sample
Moss et al. (2022)	Canada	323 (M 58%; F 42%) Age range: N/A	Qualitative	Word association task	PB milk analogs
		88 (M 56%; F 44%) Age range: N/A	Quantitative	Overall liking	6 unflavoured PB milk analogs (soy, almond, oat, coconut, cashew, pea)
		80 (M 57%; F 43%) Age range: N/A	Quantitative	Overall liking	4 flavored PB milk analogs (chocolate and vanilla flavor oat samples + chocolate and vanilla flavor almond samples)
Gorman et al. (2021)	Canada	116 (M 43%; F 57%) Age range: 18–69 years	Quantitative	- CATA (descriptive) - Liking for appearance, flavor, mouthfeel + overall liking	3 PB milk analogs (soy, almond, oat) and cow milk
Pointke et al. (2022)	Germany	159 (M 30%; F 70%) Age range: 18–70 years Dietary style: Omnivorous 22%; Flexitarian 39%; Vegetarian 28%; Vegan 11%	Quantitative	- Questionnaires - RATA - Overall liking	PB milk (oat)
Part et al. (2023)	Estonia	9 (gender: N/A) Age range: 22–43 years	Quantitative	Descriptive (sensory profile)	25 commercial PB yogurt analog samples: 2 lupine, 10 soy, 9 oat, 4 coconut
Brückner-Gühmann et al. (2019)	Germany	102 (M 50%; F 50%) Age range: N/A	Quantitative	*Blind condition:* - Expected liking for visual appearance, flavor, texture, and overall quality + overall liking - Purchase intention	2 Oat-protein enriched yogurts (nutritional claims: "source of proteins" and "high in proteins")

(Continued)

TABLE 3 (Continued)

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
				- Expected preferred sample - Actual liking visual appearance, flavor, texture + overall liking - CATA (descriptive) - Purchase intention - Preferred sample *Informed condition:* - Actual liking visual appearance, flavor, texture + overall liking - CATA (descriptive) - Purchase intention - Preferred sample	
Jaeger et al. (2023)	New Zealand	338 (M 50%; F 50%) Age range: 18–65 years	Quantitative	*Blind condition:* - Overall liking - Circumplex-inspired emotion questionnaire (CEQ) - CATA (descriptive) CATA for holistic and conceptual perceptions *Informed conditions (factual health* vs. *environmental benefit information):* - Overall liking - Circumplex-inspired emotion questionnaire (CEQ) - CATA (descriptive) - CATA for holistic and conceptual perceptions	9 commercial PB yogurts
Greis et al. (2020)	Finland	12 (Gender: N/A) Age range: N/A	Quantitative	Descriptive (sensory profile)	5 unflavoured PB yogurts + 2 cow's milk yogurts (2.5% and 4% fat content level)
		87 (M 12.5%; F 87.5%) Age range: 20–59 years	Quantitative	- TDS on textural attributes - Liking for mouthfeel + overall liking - Questionnaires	
Grasso et al. (2020)	Ireland	25 (Gender: N/A) Age range: N/A	Quantitative	- Liking for appearance, odor, flavor, texture + overall liking - Food neophobia	6 commercial PB yogurts: 2 soy, 1 coconut, 1 cashew, 1 almond, 1 hemp
Li et al. (2013)	China	10 (Gender: N/A) Age range: 20–40 years	Quantitative	Descriptive (sensory profile)	4 soy-based cheese spread samples
Li et al. (2020)	China	10 (Gender: N/A) Age range: N/A	Quantitative	Descriptive (sensory profile)	4 soy-based cheese under different ripening temperatures (control and 4, 10 and 15°C)
Chumchuere et al. (2000)	Thailand	14 (Gender: N/A) Age range: N/A	Quantitative	Descriptive (quantitative descriptive analysis)	1 fresh soy-based cheese and 1 fried soy-based cheese
Falkeisen et al. (2022)	Canada	100 (M 34%; F 66%) Age range: 19–65 years	Quantitative	- Liking for appearance, flavor, texture + overall liking - CATA (descriptive) - CATA for emotions	5 PB raw cheeses (cashew; coconut oil; tapioca flour; modified potato starch; palm fruit oil)
		93 (M 37%; F 63%) Age range: 19–65 years	Quantitative	- Liking for appearance, flavor, texture + overall liking - CATA (descriptive) - CATA for emotions	5 PB melted cheeses (cashew; coconut oil; tapioca flour; modified potato starch; palm fruit oil)
Pointke et al. (2022)	Germany	159 (M 30%; F 70%) Age range: 18–70 years Dietary style: Omnivorous 22%; Flexitarian 39%; Vegetarian 28%; Vegan 11%	Quantitative	- Questionnaires on behavioral attitudes - RATA - Overall liking	PB cheese (almond)

similar parameters (i.e., temperature and time), suggesting that the *sous vide* cooking technique could be used to develop meat analogs visually comparable to their meat equivalent, regardless of marinating type (Gómez et al., 2019).

As regards the taste, flavor, and aroma of meat analogs, a common disadvantage usually reported when plant proteins are used to produce meat analogs is the generation of volatile compounds from the lipid oxidation

TABLE 4 Characteristics of studies on plant-based fish and eggs analogs (M, males; F, females; N/A, not available).

References	Country	Participants' number and characteristics	Type of approach	Methodologies	Type of product
Katayama and Wilson (2008)	USA	14 (gender: N/A) Age range: N/A	Quantitative	Descriptive (sensory profile)	Textured soy protein samples with vegetable shrimp flavors (0%−22.3% concentrations) with different extruded-shapes (narrow die, wider die, shred-shaped strips, and 1-cm crouton-shaped bits)
Kohrs et al. (2010)	USA	10 (M 40%; F 60%) Age range: 22–30 years	Quantitative	Descriptive (quantitative descriptive analysis)	Yellow cake formulated with two different egg replacers: 1) Gum guar, whey protein isolate and wheat starch 2) Xanthan gum, whey protein isolate and wheat starch
		104 (M 45%; F 55%) Age range: 18–80 years	Quantitative	Overall liking	Yellow cake formulated with xanthan gum, whey protein isolate and wheat starch

of unsaturated fatty acids that contribute to the formation of unappealing odors and flavors (Fiorentini et al., 2020).

To overcome this problem, meat analogs formulations with flavoring mixtures with spices, seasonings, and enhancers can be produced to replicate the typical flavor of meat and/or mask the aromas associated with pulses, such as beany, grassy, or green aroma (Fiorentini et al., 2020). In this context, Gómez et al. did not find significant differences in hedonic scores for odor parameters of intensity, persistence, and overall aroma between beef and meat analog samples, independently of the marinade type used (i.e., teriyaki sauce or beer).

Katayama and Wilson (2008) determined the most liked concentration of vegetable-based chicken flavor added to soy formulations prepared in four different shapes (narrow and wide strips, shred, and bit) and with two cooking methods (deep fat-fried and baked). The authors performed both descriptive and hedonic evaluations. The sensory attributes evaluated for the chicken-flavored textured soy protein products (TSP) were mainly related to aroma/flavor and taste characteristics, such as beany flavor/aroma, oily flavor/aroma, chicken flavor/aroma, and saltiness. Moreover, color, crispiness, and chewiness attributes were also investigated. Results showed that 4% flavoring enhanced the samples' overall saltiness, chicken flavor, and crispiness. As expected, attributes like color, texture, and oily flavor were clearly influenced by the different shapes and cooking methods. In particular, the different shape of the samples was related to different moisture content and to the encapsulation of flavor molecules thanks to air pockets resulting in the frying process. Moreover, to collect more specific information regarding the consumer acceptance of meat analogs, the authors combined the descriptive analysis with a preference test with 125 consumers, who evaluated the TSP with 22.3% of chicken flavor in 1-cm crouton-like-shaped bits-type (BIT) presented as fried or baked. Overall, 66% of consumers selected as preferred the fried BIT compared to the baked BIT (Katayama and Wilson, 2008).

Two preference tests were performed in a recent study by Cordelle et al. (2022). In the first experiment, three recipes (white sauce, chop suey, and lasagna), each prepared with two or three different plant protein meat substitutes (soy or a mix of wheat and chickpea) or with meat (veal, chicken, or ham), were evaluated by 91 consumers applying the Check-All-That-Apply (CATA) method associated with the measurement of the overall liking score. The meat version was always preferred, well separated from the other products, and described by attributes such as meat and ham flavor, and dry, firm and tender texture. Recipes with plant-based protein products were less appreciated and were characterized as having vegetable and spicy aromas (Soy2) or being described as tasteless, gelatinous, and spongy (wheat-chickpea and Soy1). The authors demonstrated that it was possible to improve the acceptability of wheat-chickpea products by adding meat flavor, which positively affected the variants no longer perceived as tasteless. On the contrary, changing its color did not affect liking scores. Then, a single recipe (i.e., white sauce with quinoa as a side dish), was selected and cooked either with chicken chunks or with three different plant-based protein chunks: an optimized variant of one of the meat substitutes (i.e., wheat-chickpea with meat flavor) and two commercially available meat-substitutes based on wheat-soy and mycoprotein. Sixty-nine consumers took part four sessions, evaluating a full portion of each product during four different meals. (i) Visual liking before the tasting; (ii) Multiple-intake Temporal Dominance of Sensations (TDS) of taste, flavor, and texture descriptors, alternating with liking scales; (iii) Taste, texture, and overall liking after tasting were collected during each session. Concerning visual liking, the optimized variant obtained the highest mean score. However, the overall liking assessed after tasting, as the strongly correlated taste, and texture liking, showed that the products formulated with mycoprotein and chicken obtained higher scores than the wheat-chickpea with meat flavor. Indeed, this sample was more appreciated for its taste but less for its texture. Herein consumers were dissatisfied with their expectations since visual liking did not reflect the after-tasting overall liking. Concerning the dynamic liking measurements, the

authors reported that data obtained from dynamic and non-dynamic measurements were comparable, suggesting that product's hedonic scores were not affected by the temporality (Cordelle et al., 2022). Nevertheless, the dynamic approach primarily highlighted that meat substitutes could be attractive in their appearance and tasty with the addition of "meat aroma" but should be improved for the texture descriptors: tenderness seemed to be a positive characteristic, whereas a spongy texture was less accepted. Thus, even more challenging, is to successfully mimic the texture of animal proteins and their unique functional properties.

In this context, a recent study specifically focused on texture, investigating in commercially available meat analogs the connections among structure, textural characteristics, sensory evaluation, and consumer acceptance (Godschalk-Broers et al., 2022). The authors screened more than 8,000 meat analogs marketed from 2014 to 2019. Availability and variety in composition concerning protein type, total fat content, and fiber were the factors that guided the product selection. Thirteen plant-based chicken pieces and 14 plant-based burgers were chosen as representative samples and compared with real chicken pieces and a beef burger as reference samples. Seventy-one non-vegetarian adult consumers performed hedonic and descriptive evaluations on the samples stored and prepared by the participants at home, according to the provided guidelines. Although the differences were product-dependent, the analog chicken pieces generally obtained higher scores in color (darker) and fattiness and lower in texture parameters like hardness, cohesiveness and fibrousness, and in meaty flavor compared to real chicken. On the contrary, a clear sensory pattern was not observed for the texture characteristics of juiciness, chewiness, and overall flavor intensity, which scored higher in some chicken analogs and lower in others than real chicken. Regarding burger samples, juiciness and fattiness were the attributes that distinguished natural beef from analogs, which were scored lower in chewiness, cohesiveness, fibrousness, juiciness, fattiness, and with a lower flavor intensity and meaty flavor. For both chicken pieces and beef burger analogs, overall liking was related to meaty flavor and juiciness. However, the authors noted that liking for flavor is guided especially by the type of flavor, rather than its intensity. As well, juiciness is reported to be the most crucial mouthfeel attribute to focus on when plant-based burger development is planned. For chicken analog pieces, fibrousness and cohesiveness also played a role. The instrumental analysis highlighted that the source of juiciness in meat analogs is not only related to measurable characteristics, such as moisture content and expressible moisture but arises from a combination of aspects linked to both samples' composition and structure (Godschalk-Broers et al., 2022).

Improving simple texture attributes may not be an efficient strategy to increase the consumers' appreciation of meat analogs, while taking into account the complex interplay of sensory properties with cross-modal interactions sounds more promising. Moreover, repeated exposure could be another valid approach to establishing a durable meat replacement with new substitutes. Hoek et al. (2013) tested a long-term in-home use test of 10 weeks in realistic conditions, with twice-a-week consumption of selected meat substitutes (i.e., tofu and Quorn) or a reference meat product (chicken). They considered the role of the product, the person, and the meal context in studying consumer acceptance over time. Results showed that repeated exposure to food products that are relatively unfamiliar and distinct (like meat substitutes) might increase acceptance by a segment of consumers (i.e., participants who liked the product better over time vs. participants who showed a reversed reaction and got bored) (Hoek et al., 2013) and repeated exposure can decrease the desired similarity to meat (Hoek et al., 2011). However, to improve the long-term acceptance of these products, it is essential to focus mainly on establishing positive initial product experiences: indeed, whether initial liking is low compared to familiar products such as meat, most consumers will hardly ever consume these products again (Hoek et al., 2013). Moreover, stressing taste information on food labels (i.e., information that a veggie burger is especially tasty) may affect food choices and willingness to purchase more sustainable foods.

3.1.3. Studies involving specific population targets

Participants' age, gender, ethnicity and/or the type of diet followed may influence plant-based meat analogues' sensory quality. However, few studies are available on the perception and acceptance of specific population targets toward these products.

In this context, Pater et al. (2022) involved 8- to 10-year-old non-vegetarian Dutch children recruited in primary schools and investigated their perception/attitudes toward plant-based meat analogs (i.e., commercial vegan burgers and vegetarian balls based on soy and/or wheat) through semi-structured interviews. The study highlighted that the consumption of meat analogs was quite high among children (1 to 2 times per week), and most of them were generally willing to try these products. During the interviews, most children discussed meat analogues' palatability, reporting perceiving them as tasty. Approximately half of the children mentioned that the overall appearance of a meat analog should resemble meat, while someone mentioned that the analogs should have a color much more associable with vegetables (i.e., a greenish color). When it came to taste, the meat analog was preferred if had a resemblance to real meat and had taste/flavors like sweet, salty, spicy, or seasoned. The texture of the meat analogs should resemble meat and would be preferred as juicy inside and crispy or crunchy outside.

Moving to the elderly population, Grasso et al. (2021) explored through surveys the attitudes of this consumer target in five European countries. Through a segmentation analysis constructed on meat liking scores and cooked meat consumption, three segments of older consumers were identified: heavy vs. medium vs. light meat consumers among 2,500 community-dwelling older adults aged 65 years or above in Finland, Poland, Spain, the Netherlands, and the United Kingdom. The segments showed different reasons for liking and disliking meat and plant-based "meat" substitutes, and the authors highlighted that the importance of sensory appeal, resemblance to meat and familiarity with plant-based products is associated with being heavy meat consumers. Elderly-oriented product developers should address familiarity with alternative protein sources and sensory appeal in communication strategies to incentivise elderly heavy meat consumers in the transition toward sustainable food systems (Grasso et al., 2021). The study also reported the presence of cross-national differences in terms of pro-environmental protein

consumption and attitudes (i.e., heavy meat consumers living in the Netherlands vs. medium meat consumers living in Poland), but no differences regarding acceptability or sensory perception have been highlighted between countries, as previously reported also by Hoek et al. (2013).

Concerning gender, women are reported to be light meat consumers (Grasso et al., 2021), to have a better predisposition for meat alternatives than men, mainly due to their concerns about animal welfare and the environment (Michel et al., 2021), and to be more prone to change their eating habits compared to men (Piester et al., 2020). However, any further gender-related comparison cannot be done in terms of sensory acceptance or rejection of plant-based meat, because no data are available on this topic.

As regards diet styles, it has been reported that omnivores and meat likers tend to judge sensory characteristics as unsatisfactory in meat analogs because unpleasant or unexpected tastes do not respond to their expectations, representing a barrier to acceptance (Hoek et al., 2011; Elzerman et al., 2013; Hellwig et al., 2022; Kerslake et al., 2022). In this context, Pointke et al. (2022) recruited 159 German consumers with different dietary styles (omnivore, flexitarian, vegetarian, vegan), who performed a sensory evaluation on three different plant-based commercial products (milk, cheese, and salami) applying the rate-all-that-apply (RATA) approach and assessing the overall liking of each product on a 9-point hedonic scale. As expected, vegans rated overall liking significantly higher than omnivores. However, differences in product descriptions also emerged, as sensory terms frequency of selection and sensory profiles of the three plant-based alternative products varied according to the dietary styles. These differences were more pronounced in the oat drink and plant-based cheese. Regarding plant-based salami, omnivores rated significantly lower the intensity of "meat smell" and "meat taste" compared to others.

3.2. Dairy analogs

3.2.1. Studies' characteristics

An overview of the characteristics of the 26 studies on dairy analogs included in this review is provided in Table 3. The studies were published from 2000 to 2023, and the majority ($n = 17$) investigated plant-based milks (Chambers et al., 2006; N'Kouka et al., 2006; Palacios et al., 2010; Lawrence et al., 2015; Pramudya et al., 2019; Gorman et al., 2021; Jaeger and Giacalone, 2021; Oduro et al., 2021; Vaikma et al., 2021; Cardello et al., 2022; Chung et al., 2022; Moss et al., 2022; Pointke et al., 2022), or fermented beverages obtained from pulses (Cosson et al., 2020; Laaksonen et al., 2021; Mefleh et al., 2022; Aydar et al., 2023), five plant-based yogurt (Brückner-Gühmann et al., 2019; Grasso et al., 2020; Greis et al., 2020; Jaeger et al., 2023; Part et al., 2023), and five cheese-analogs (Chumchuere et al., 2000; Li et al., 2013, 2020; Falkeisen et al., 2022; Pointke et al., 2022). Nine studies were conducted in Europe (Brückner-Gühmann et al., 2019; Cosson et al., 2020; Grasso et al., 2020; Greis et al., 2020; Laaksonen et al., 2021; Vaikma et al., 2021; Mefleh et al., 2022; Pointke et al., 2022; Part et al., 2023) and Turkey (Aydar et al., 2023). Six research articles were conducted in the US (Chambers et al., 2006; N'Kouka et al., 2006; Palacios et al., 2010; Lawrence et al., 2015; Pramudya et al., 2019; Jaeger and Giacalone, 2021), three in Canada (Gorman et al., 2021; Falkeisen et al., 2022; Moss et al., 2022), and two in New Zealand (Cardello et al., 2022; Jaeger et al., 2023). To note, four studies were conducted in Asia (Taiwan, Chung et al., 2022; China, Li et al., 2013, 2020; Thailand, Chumchuere et al., 2000) and only one in Africa (Republic of Ghana, Oduro et al., 2021).

As regards the target population and methodological approach, all the studies focused on the adult population, except one with children (Palacios et al., 2010), and applied a quantitative approach. Four studies applied hedonic methods (Palacios et al., 2010; Grasso et al., 2020; Jaeger and Giacalone, 2021; Oduro et al., 2021), while the majority used a descriptive method (i.e., Quantitative Descriptive Approach, Sensory Profile, Rapid descriptive methods like CATA or RATA, TDS) (Chumchuere et al., 2000; Chambers et al., 2006; N'Kouka et al., 2006; Li et al., 2013, 2020; Cosson et al., 2020; Vaikma et al., 2021; Mefleh et al., 2022; Part et al., 2023), generally in combination with hedonic evaluations and/or surveys (Lawrence et al., 2015; Brückner-Gühmann et al., 2019; Pramudya et al., 2019; Greis et al., 2020; Gorman et al., 2021; Laaksonen et al., 2021; Cardello et al., 2022; Chung et al., 2022; Falkeisen et al., 2022; Pointke et al., 2022; Aydar et al., 2023; Jaeger et al., 2023). Only Moss et al. (2022) applied a mixed experimental design (i.e., qualitative and quantitative). Four studies also evaluated liking associated with the emotion elicited during product consumption (Jaeger and Giacalone, 2021; Cardello et al., 2022; Falkeisen et al., 2022; Jaeger et al., 2023).

3.2.2. Analysis of the hedonic and perceptive determinants of dairy analogs

Given the larger number of articles available in the literature for this product category compared to meat analogs, this paragraph is organized in different sections focused on plant-based milk, yogurt and cheese analogs, respectively.

3.2.2.1. Plant-based milk analogs

Plant-based milk analogs are water-soluble extracts of cereals, pseudo cereals, legumes, oilseeds, and nuts, which after wet milling, filtration, the addition of ingredients, sterilization, and homogenisation, result in an emulsion that resembles cow's milk (Reyes-Jurado et al., 2021). They are usually classified based on their primary ingredient. Soy-based and almond-based milk alternative are the most consumed, although in the last years, other sources have gained popularity, and the market of plant-based milk alternatives has expanded in Europe and US, totalling € 2.2 billion and $ 2.8 billion in sales, respectively (The Good Food Institute, 2022).

These products are well-established as beverages and, recently, have been extensively utilized in recipes as an ingredient for ice cream, yogurt, creamer, cheese, butter, and salad dressing (Sethi et al., 2016). However, although consumer interest in and demand for these products is growing, there are still many alternatives that consumers consider unacceptable because fail to mimic the sensory properties of cow milk. In fact, their appearance is often different from creamy-white cow milk's appearance due to their raw materials and could be characterized by a greenish, grayish, or brownish color and different clarity (Pramudya et al., 2019; Aydar

et al., 2023). Sometimes, these differences do not affect consumers' liking (Tangyu et al., 2019; Reyes-Jurado et al., 2021), while in other cases, they may negatively impact overall liking (Pramudya et al., 2019; Moss et al., 2022).

Generally, the sensory evaluation of plant-based milk alternatives has demonstrated a deficiency of this kind of product regarding odor/flavor and taste. In this context, Cardello et al. (2022), segmented into four clusters of 345 consumers from New Zealand based on their liking for cow's milk or plant-based milk samples. Results showed that, as expected, among all the investigated factors in the tested dairy and plant-based beverages, sensory attributes and especially flavor, were more potent drivers of liking among different segments of consumers. Moreover, flavor liking seemed to be affected by food neophobic attitudes, which led subjects with higher neophobia traits to less appreciate rice-based milk alternative products (Pramudya et al., 2019; Jaeger and Giacalone, 2021).

A bunch of studies described the sensory characteristics of different legume-based milk alternatives (i.e., soy, pea, chickpea, kidney beans, and lupine) and highlighted that their beany and earthy/grassy odors/flavors, related to the presence of n-hexanal and n-hexanol generated by plant lipid oxidation (Tangyu et al., 2019), characterized these beverages (Chambers et al., 2006; N'Kouka et al., 2006; Lawrence et al., 2015; Cosson et al., 2020; Laaksonen et al., 2021; Vaikma et al., 2021; Mefleh et al., 2022), and negatively affected their overall acceptance. In particular, Chambers et al. (2006) implemented the vocabulary provided by N'Kouka et al. (2006) for soymilk samples and defined twenty-eight attributes for describing a wide range of "fresh" and heat-processed soymilks. Lawrence et al. (2015) determined the sensory attributes that drive the liking of 12 commercial unflavoured soymilks among 235 US consumers. Results showed that is flavor/taste of soymilk samples and not their color that mainly influenced the overall liking. Moreover, samples that were judged to be flavored enough using Just-about-right (JAR) scale were also the most highly liked, indicating that flavor was a very important attribute to the consumers and penalized some samples for not being flavored enough. Using a similar approach, Vaikma et al. (2021) evaluated 90 plant-based beverages obtained from different raw materials and available on the Estonian market and mapped them from a sensory point of view using the RATA approach. Instrumental analysis (GC/MS/O) was combined with the sensory approach to examine further the effect of volatile compounds on the sensory properties of various products. A characterizing and stronger legume odor/flavor is described in legume-based beverages (i.e., soy), while cereal odor/flavor was typical of cereal and pseudocereal-based beverages (i.e., oat, rice, buckwheat, quinoa), with the oat samples tended to have stronger aftertaste intensity. Nut-based milk alternatives (i.e., almond, coconut, hazelnut, cashew, brazil nut) were characterized by nutty odor/flavor, while seed-based milk (i.e., hemp beverage) possessed a hay-like odor. Unacceptable sensory property, such as painty off-flavors, affected both nut- and seed-based beverages (Vaikma et al., 2021). These off-flavors are derived from the oxidation of the lipids, which leads to the formation of the hexanal and pentanal volatile compounds (Tangyu et al., 2019; Vaikma et al., 2021). Pramudya et al. (2019) evaluated the rice-based milk alternatives commercially available in the US market, identifying 23 sensory attributes and determining which affect the consumer acceptability of these products. In particular, higher ratings of sweetness, astringency, nutty and grainy flavors are associated with increased overall liking, which contrarily decreased when dark color, yeasty/fermented and starchy aromas, yeasty/fermented and cardboard flavors, and bitter and sour tastes scored higher. The attributes associated with vanillin were of particular interest: vanilla aroma (i.e., ortho-nasal odors) was negatively associated with samples' overall liking, while the flavor (i.e., retro-nasal odors) seemed to positively impact overall liking. The authors commented on this discrepancy, suggesting that an odor like vanilla, perceived ortho-nasally, could be an unfamiliar and unexpected attribute in rice-based beverages, contributing to a decrease in consumers' liking. On the contrary, when perceived retro-nasally, could play a crucial role in masking the presence of undesirable flavors and in increasing sweetness perception through multimodal sensory integration, as previously suggested in other food and beverages (Proserpio et al., 2021).

When it comes to taste and tactile sensations, plant-based beverages were reported being characterized by bitter off-taste, sour taste and metallic or astringency sensations, which are usually related to the presence of phenols, terpenes, glycosylates, glucosinolates, and flavonoids (Tangyu et al., 2019). The presence of these compounds may explain consumers' dislike for this kind of product when added to coffee. For instance, two studies by Gorman et al. (2021) and Chung et al. (2022) aimed to identify sensory drivers of liking of plant-based milk coffees (i.e., oat, soy, almond, and coconut) in Canadian and Taiwanese consumers, respectively. Results of both studies suggested that for all consumers, the more similar a plant-based milk coffee was to dairy milk coffee, the more positive sensory experiences were perceived. Pungent, grassy, rancid oil, earthy and beany flavors and sensations like sour, greasy and astringency weakened the acceptability of the coffee samples.

To overcome the sensory issues the application of thermal treatments on the plant-based extracts prior to "milk" extraction could be a strategy to eliminate the off-taste and off-flavors (Reyes-Jurado et al., 2021). Moreover, to increase consumer acceptance, plant-based alternatives may include flavoring (e.g., chocolate and vanilla) (Moss et al., 2022) or may be sweetened by adding sugars (Aydar et al., 2020; Reyes-Jurado et al., 2021). In the study proposed by Moss et al. (2022), the acceptability of flavored (chocolate and vanilla) and unflavoured plant-based milk analogs (almond and oat) was evaluated. Consumers' liking scores were significantly improved by adding the vanilla and chocolate flavoring, and the chocolate version was liked significantly more than the unsweetened samples. These results highlighted that flavoring could improve the liking of the oat and almond milk, and the authors suggested that it may be able to improve some of the negative sensory attributes associated with other nut-based milk alternatives, as well as soymilks.

Texture or mouthfeel issues also influence plant-based milk alternatives, which can present a chalky, grainy or gritty mouthfeel sensation due to the possible presence of large particle aggregates (Tangyu et al., 2019). Cereal and pseudo-cereal beverages tend to have a waterier texture when compared to other product categories (Pramudya et al., 2019), while nut-based beverages may possess a thicker and lumpier texture (Vaikma et al., 2021).

Other strategies to overcome off-flavors and contemporary succeed in obtaining a smoother texture include blending different

plant-based milks. To cite a clear example, in a study performed in Ghana by Oduro et al. (2021), a Relative Preference Mapping approach was used to identify innovations in three-blend plant-based milk alternative formulations obtained from raw plant materials, such as melon seeds, peanuts, coconuts and tiger nuts. In addition to the 6 prototypes of 3-blend plant-based milk alternatives, commercial soymilk and sweetened UHT milk were included in the product set. As expected, the two commercial products (i.e., sweetened UHT milk and soymilk) were liked more than the reformulated plant-based milk alternatives. Nevertheless, two blended samples (i.e., Sample 1: Tiger nuts 37.5%, Coconuts 25%, Peanuts 37.5%; Sample 2: Tiger nuts 25%, Coconuts 50%, Peanuts 25%) were reported having a good chance of success being considered acceptable by consumers, while the products with melon seeds milk were found to have the lowest acceptability. Recent scientific literature dealing with plant-based milk blending is scarce or presents some critical issues with the experimental design (e.g., the use of trained assessors to evaluate the acceptability of the products), thus, further studies are needed.

3.2.2.2. Plant-based yogurt analogs

The aforementioned concerns and strategies are also appropriate to improve plant-based yogurts' sensory properties, though there is significantly less literature on the latter than on milk alternatives. A few studies investigated this product category's sensory profile (Brückner-Gühmann et al., 2019; Grasso et al., 2020; Greis et al., 2020; Part et al., 2023). Part et al. (2023) sourced twenty-five samples of four plant-based yogurt alternatives (i.e., coconut, soy, lupin and oat) from retail stores in Estonia, Finland, and Germany and applied a descriptive sensory analysis on odors and tastes. Coconut-based yogurt was the most distinctive product presenting an intense raw material odor and taste and low bitterness and astringency. Soy samples had higher sourness and raw material odor/taste. More variation was observed within the oat yogurts, as some samples were perceived as sweet, while others were salty, astringent, and bitter, and a couple of samples also had some cheesy and fermented odors.

A matter often reported in the literature is that the texture and mouthfeel perception of plant-based yogurts are critical drivers for consumer acceptability (Brückner-Gühmann et al., 2019; Grasso et al., 2020; Greis et al., 2020) due to different concentrations and properties of plant proteins, which usually require the addition of gelling agents to mimic the same gelation properties of casein (Brückner-Gühmann et al., 2019). For instance, Grasso et al. (2020) analyzed six commercially available plant-based yogurts made from coconut, soy, cashew, hemp and almond, and a cow milk yogurt as a benchmark. The sensory analysis demonstrated that the texture of coconut and soy yogurts was perceived as equivalent to the one of cow milk yogurts and the samples were equally appreciated, probably due to specific additives in the formulations (i.e., hydrocolloids, sweeteners, and flavors). Greis et al. (2020) analyzed the mouthfeel properties (thick, thin, creamy, watery, sticky, and foamy), overall liking and mouthfeel liking of five oat-based yogurt-like products and two cow milk yogurts using temporal dominance of sensations (TDS) with 87 Finland consumers. Attributes typically used to describe dairy yogurts were also relevant for describing non-dairy yogurt alternatives, and thickness and creaminess were temporal drivers of liking, while thinness and wateriness were temporal drivers of disliking. The importance of creamy attributes in oat-based products was also highlighted by Brückner-Gühmann et al. (2019). The authors developed two types of fermented products based on oat protein concentrate and performed a consumer test with one hundred and two participants in Germany. Results showed that the creamy attribute in the oat-based gels increased the overall liking, while the consumers disliked sour, chalky, and floury attributes.

Because of the poor sensory quality generally associated with most plant-based yogurts, marketers have spent much effort working on extrinsic variables, such as branding, packaging, labeling, and information related to benefits for health, animal and environment, as a strategy to improve consumers' consumption, acceptability and attitudes toward these products. In this context, Jaeger et al. (2023) examined the real impact of health or environmental/sustainability information related to the consumption of plant-based yogurts on consumer acceptance, sensory characterization (appearance, taste, and texture), emotional response, attitudinal associations, and holistic and conceptual perceptions. Thus, a consumer study was conducted with 338 participants who tasted eight commercially available vanilla-flavored plant-based yogurts from different raw materials, both pure and blended (i.e., soy, coconut, cashew). Three experimental conditions were designed: (i) blind, with participants receiving no information about the yogurt samples; (ii) informed about the personal health benefit, with participants receiving information about health benefits associated with plant-based yogurts or foods; (iii) informed about the environmental benefit, with participants receiving information about environmental benefits associated to plant-based yogurts or foods. Results showed that all the plant-based yogurt samples were scarcely appreciated (i.e., liking scores between 4 and 6 on the 9-point scale), and the health and environmental information minimally impacted the liking of the samples. Taken together the results suggested that providing health and environmental benefit information for positively influencing consumers' judgements of plant-based yogurts is not an effective approach when the perceived sensory product quality is poor.

3.2.2.3. Plant-based cheese analogs

An even worse situation in terms of data availability exists for plant-based cheeses. The majority of literature is limited to soy-based products and indicates, as the main soy-based cheeses concern, the characteristic beany flavor and a gritty mouthfeel, probably caused by the sedimentation of large particles (Chumchuere et al., 2000; Li et al., 2013, 2020). Moreover, Falkeisen et al. (2022) investigated how consumers evaluated 10 plant-based cheeses (i.e., five raw and five melted samples) purchased from local grocery stores in terms of sensory characterization, liking and emotional responses. The results showed that participants did not like the flavor or textural properties of the samples proposed, which barely exceeded the middle point of the hedonic scale (anchored as 1 = Dislike Extremely, 5 = Neither Like nor Dislike, 9 = Like Extremely). The participants preferred plant-based cheeses that were buttery, smooth and soft attributes, which are the main sensory characteristics that drove consumer liking. On the contrary, samples that were mouthcoating, rubbery, pungent and had off-flavors were the most disliked by consumers. Moreover, samples with higher overall liking scores were associated with positive

emotions, while the least liked sample was associated with negative ones, suggesting how the emotional responses are linked to and could reinforce participants' hedonic responses.

3.2.3. Studies involving specific population targets

As highlighted previously for meat analogs, many person-related factors impact the acceptance of plant-based beverages. In this context, several studies have investigated different segments of consumers with distinct attitudes toward dairy analogs. As expected, the dietary style influences the sensory perception of dairy analogs. The study by Pointke et al. (2022), detailed above, showed that the frequency of selection of sensory terms and the sensory profiles of dairy alternative products (i.e., oat milk and plant-based cheese) differed according to the dietary styles. It is noticeable for the oat drink that vegans never used "bitter taste" and "sour taste" attributes to describe the sample. For the plant-based cheese, the "cheese smell" was perceived as significantly more intense by the flexitarians. On the other hand, the "broth odor" and "umami taste" intensities were rated significantly lower by the omnivores.

Pramudya et al. (2019) investigated the acceptability of commercially available rice-based milk alternatives in about 100 US consumers. The authors did not report any differences in consumer liking of rice milk samples as a function of demographic variables, such as gender, age group (19–74 y.o.), ethnicity (i.e., Caucasians, Asians, Latinos, African Americans, Native Americans), annual household income, or frequency of consumption have been highlighted. Accordingly, in a large-scale study performed by Palacios et al. (2010), on a total of 893 lactose-tolerant and lactose-intolerant Caucasian, African-American and Hispanic adult consumers (ages 18–64 years) who evaluated the liking of lactose-free cow's milk and soy-based beverages, no effect on overall liking was found for ethnicity, age, gender, or lactose tolerance/intolerance. On the contrary, in the study performed by Lawrence et al. (2015), 12 commercial unflavoured soymilks were selected and evaluated by 225 U.S. consumers divided into three age/ethnicity categories: Caucasian/African American females aged 18–30 years, Asian females aged 18–30 years, and Caucasian/African American females aged 40–64 years. The authors reported that age did not impact soymilk liking, but ethnicity did, with Asians judging soymilks differently and with lower liking scores than Caucasians/African Americans. However, the authors hypothesized that the differences in hedonic scores could be due to the tendency for Asians to be less likely to use extreme ends of the hedonic scale than Westerners, as previously documented (Prescott et al., 2002).

As emphasized for the meat analogs, few data are available on the perception and attitudes of other population targets (i.e., children and elderly) toward dairy analogs. To the best of our knowledge, the study by Palacios et al. (2010) was the unique addressing preference mapping of soymilks with U.S. children aged 8–16 y.o. of three ethnicity categories: Caucasian, African American, and Hispanic. The authors conducted a consumer hedonic test on unflavoured and chocolate-flavored lactose-free dairy milk vs. unflavoured and chocolate-flavored soymilk. Results showed that flavored lactose-free cow's milk was more appreciated than flavored milk substitute beverages. No differences in hedonic scores occurred in different ethnic groups (Caucasian, African American, Hispanic), but a large difference emerged by age group, with reduced criticism by younger respondents regarding less acceptable products.

3.3. Fish and eggs analogs

3.3.1. Studies' characteristics

An overview of the characteristics of the two studies on fish and eggs analogs included in this review is provided in Table 4. The studies were published in 2008 and 2010, one focused on plant-based fish (Katayama and Wilson, 2008) and the other one on plant-based eggs (Kohrs et al., 2010). Both studies were conducted in the US and employed a quantitative approach involving adults: Katayama and Wilson (2008) performed a descriptive analysis, while Kohrs et al. (2010) applied a combination of descriptive and hedonic methods.

3.3.2. Analysis of the hedonic and perceptive determinants of fish and eggs plant-based analogs

In comparison to meat or dairy analogs, the number of products developed to mimic real fish and eggs is much lower (The Good Food Institute, 2022) and, consequently, there are very few dated articles dealing with these analogs. Katayama and Wilson (2008) investigated, as a fish analog, texturised soy protein added with two powdered flavors made from non-meat derivatives to mimic shrimp flavors (crab-like and oyster-like characteristic flavors). The oyster-like flavor was used in single or in combination with crab-like flavor. For each formulation, either a low (16.7%) or high (22.2%) concentration was chosen. A descriptive method was applied to evaluate beany flavor/aroma, fishy flavor/aroma, shrimp flavor/aroma, saltiness, crispiness, and color. Results showed that the two different flavor concentrations (low or high) led to differences in fish and shrimp flavor and saltiness. However, researchers pointed out that whatever flavor was used, during shelf-life, fishy flavor and aroma increased, while shrimp flavor and aroma decreased thus reducing their storage time. Instead, using single or combination flavor formulations produced differences in crispness. Variations in product texture was also confirmed by instrumental texture analysis.

Egg substitutes are developed to replicate the functional properties of eggs (i.e., emulsification, coagulation, foaming, and gelling) in the food recipe. Substances used as egg replacers are whey protein and several gums and can be employed not only to prepare recipes for vegan consumers but also to produce foods with low cholesterol, an increased shelf-life and that do not require refrigeration for storage (Kohrs et al., 2010). Kohrs et al. (2010) used these substances in blend, combining whey protein isolate and wheat starch with guar or xanthan gum in a yellow cake system. The two formulations with egg replacers were then compared to the control cake with whole-egg through quantitative descriptive analysis (QDA) and consumer acceptability test. A trained panel of 10 judges evaluated the cake samples based on six descriptive terms (crust stickiness, color, springiness, moistness,

firmness, and egg flavor). Results showed that the formulation with xanthan gum or guar gum differed from the control cake in terms of surface stickiness, crumb yellowness and egg flavor. Authors hypothesized that the surface stickiness was due to an instability of the foam that led to a small portion of moisture, which usually accumulates at the bottom of the pie, migrating to the crust. Regarding springiness, moisture and firmness no significant differences were found between the formulation with xanthan mix and the control cake. However, although there were no significant differences for the xanthan-containing formulation, the use of egg replacers decreased the foaming properties of whey protein and increased cake moisture. Following descriptive analysis, researchers conducted a consumer acceptance test with 104 consumers to assess differences in appearance, texture, flavor, and overall acceptability between the control cake and the one formulated with xanthan gum. Interestingly, in all attributes assessed, the xanthan gum formulation scored higher than that of the control cake, suggesting the technological potentiality of this formulation.

No studies are available on specific population targets for fish and eggs analogs.

4. Discussion

This review provides an up-to-date overview of the studies focused on sensory properties and overall liking of plant-based substitutes of animal-origin products, including meat, dairy, fish and eggs analogs, with emphasis on those dealing with specific population targets.

Although the literature review showed that all sensory dimensions are influenced by the replacement of animal proteins with those of vegetable origin, it emerged that the relative importance of appearance, odor, taste, and texture varies according to plant-based analogs category, as summarized in Table 5. For example, meat analogs (also already commercially available in various European markets) should be especially improved for their texture descriptors, since consumers look for juiciness, and elasticity/firmness, similar to their animal-based counterparts. This is particularly true when plant-based burger development is planned because juiciness is considered the most crucial mouthfeel attribute to focus on. As well, as in chicken analog pieces, for which fibrousness and cohesiveness also played a role. Nevertheless, it has to be considered that improving simple texture attributes may not be a sufficient and efficient strategy to increase the consumers' appreciation of meat analogs while taking into account the complex interplay of sensory properties with cross-modal interactions sounds more promising. Indeed, these products should be attractive in their appearance and have a great resemblance with real meat. Moreover, the meat aroma/flavor should be another characteristic to consider in order to make consumers judge the product as "tasty."

For milk analogs, darker/greenish colors may negatively affect consumers' liking, although the aromas and flavors imparted by the raw materials are the sensory characteristics that play the major role in driving consumers' overall liking. For the two other dairy analogs, like plant-based yogurts and cheeses, a matter often reported in the literature is that their texture and mouthfeel perception are the most critical drivers for consumer acceptability. A uniform, creamy and thick texture should characterize plant-based yogurts, while buttery, smooth and soft attributes are searched by consumers in plant-based cheeses. Moreover, bitter off-taste, sour taste and metallic or astringency sensations, mostly derived from the raw materials, should be controlled during the production.

To solve some of the abovementioned challenges, different manufacturing strategies have been suggested which are reported in Table 5. In general, the mitigatory processing strategies to mask off-odors and flavors consist of using flavoring agents and/or sweeteners as well as applying mechanical and thermal pre-processing. The use of hydrocolloids and gelling agents as well as the application of separation and/or enzymatic hydrolyzation of lipids and starch and homogenisation to disrupt larger particles and lipid droplets are among the processing strategies mainly used to improve texture parameters. Similarly, color challenges that characterize plant-based analogs may be tackled using colorants. However, the "health issue" related to the use of multiple ingredients/additives, is one of the fundamental aspects that let or not consumers choose analogs over real meat or dairy products, since their nutritional value is still under debate in the consumer's mind. The use of additional ingredients and additives should be combined with the implementation of process operations suited to the ingredients in order to obtain a plant-based food similar to the animal version. Regarding plant-based meat, the most common methods are the spinning technique and extrusion cooking under high and low moisture conditions (Singh et al., 2021). These techniques allow the formation of meat-like fibrous structures, thus contributing to the bite-feeling, elasticity/firmness and sensory attributes of the product (Ahmad et al., 2022). For plant-based milk, in addition to more classical techniques such as homogenisation and pasteurization, more innovative techniques are being developed such as for example, high-intensity ultrasound, high-pressure processing, pulsed electric field, supercritical carbon dioxide, ultraviolet radiation, microwave heating, and ohmic heating (Bocker and Silva, 2022). In general, these innovative heat treatments have the advantage of reducing the occurrence of Maillard reactions and improving nutritional quality by preserving heat-sensitive compounds (Bocker and Silva, 2022).

Although general conclusions cannot be drawn on fish and eggs analogs as well as on specific population targets due to the still reduced number of studies, some considerations can be highlighted. Children, especially the younger ones, seem to be less critical to plant-based products and are generally willing to try and taste them, while the elderly need a certain degree of familiarity with the product (especially toward meat analogs) to appreciate them as much as their animal counterparts. Furthermore, both children and the elderly place great importance on the sensory appeal and, especially taste/flavor and texture of the meat analogs should resemble meat. Concerning gender and dietary styles, women and vegetarians/vegans are reported to have a better predisposition for plant-based analogs alternatives than men and omnivores, mainly due to their concerns about health issues, animal welfare and the environment. However, any further gender-related comparison cannot be done in terms of sensory acceptance or rejection of these products, because no data are available on this topic. Moreover, no differences regarding acceptability or sensory perception have been highlighted between countries in the analyzed studies. Only one study highlighted a difference in soymilk liking

TABLE 5 Sensory challenges characterizing plant-based products and related mitigatory processing strategies.

Plant-based products	Sensory aspects	Sensory challenges	Mitigatory strategies
Meat analogs	Appearance	Color fading	Using of marinades or colorants
	Aroma/taste/flavors	- Beany/grassy/earthy aromas and flavors - Tasteless - Aftertaste	Using of flavoring agents and seasonings
	Texture and mouthfeel	Lack in juiciness and firmness	- Using of hydrocolloids or gums to improve texture parameters - Blending different raw materials - Controlling sensory attributes through cross-modal integration
Dairy analogs	Appearance	- Greenish/grayish/ - Brownish color - Lack of clarity	Applying extended mechanical and thermal pre-processing
	Aroma/taste/flavors	- Beany/earthy aromas and flavors - Cereal aromas and flavors - Fermented/yeasty aromas and flavors - Nutty aromas and flavors - Off-flavors - Bitter and acid tastes - Astringent and metallic sensations	- Using of flavoring agents - Using of sweeteners - Applying extended mechanical and thermal pre-processing
	Texture and mouthfeel	- Watery/lumpy texture - Chalky/grainy/gritty mouthfeel - Lack of creaminess	- Applying separation and/or enzymatic hydrolyzation on lipids and starch - Applying homogenisation to disrupt larger particles and lipid droplets - Using of hydrocolloids or gelling agents to improve viscosity
Fish and eggs analogs		Insufficient available data	

between Asians and Caucasians/African Americans. However, also the authors were not confident in associating these differences in hedonic scores to the different ethnicity rather than to the tendency for Asians to be less likely to use extreme ends of the hedonic scale than Westerners.

5. Limitations

We acknowledge some limitations of the present study. Although a broad search string has been used, some studies may be missing. Considering other search engines in future literature reviews might expand the overview. Furthermore, though it is not explicitly requested in systematic reviews, we did not include a meta-analysis due to the high heterogeneity in products tested and methodological approaches. Future research may benefit from the use of consistent measures to allow a more precise and robust quantitative comparison between studies.

6. Challenges and future perspectives

The present review highlighted several challenges and gaps that need to be addressed in future research:

1) The majority of sensory and consumer studies focused on dairy and meat analogs, while there is almost no information about the exploitation of plant-based protein sources for the development of fish and eggs analogs. A better understanding of the sensory aspects that play a positive or negative role in the acceptability of this products category is certainly useful to contribute to the expansion of their market and consumption.
2) There is a lack of information on vulnerable population targets such as children and the elderly. These consumer targets have specific needs and expectations that differ considerably from those of the adult population. They are also the age groups that potentially have the highest incidence of food neophobia (Hazley et al., 2022).

- Considering that children are the consumers of the future and play a pivotal role in household food choices, they could essentially contribute to the transition toward more sustainable consumption. Moreover, older consumers are increasing in number, representing a significant portion of the global population (European Commission, 2020), with specific dietary needs (i.e., recommended daily intake of proteins), and preferences. Therefore, it is essential to deepen the study about the perceptive determinants of acceptance of plant-based analogs that could be perceived as unfamiliar by these population targets. In this context, communication about animal welfare and the environmental impact related to the consumption of plant-based analogs of animal-origin food can activate positive perceptions around these products. Moreover, understanding their perception is helpful to successfully

develop and market meat analogs that could be attractive amongst a broader population.

3) There is a paucity of studies on developing countries. At the time this review was conducted, there were no studies on meat, fish and eggs analogs carried out in developing countries, while there were few studies performed on dairy analogs in China and Africa.

    - Food perception and preference vary substantially as a function of country and socioeconomic level, therefore drawing conclusions on food products' acceptability based only on outcomes obtained from Western populations is simplistic and wrong. Improving the sensory quality of new plant-based analogs of animal-origin food might contribute to ensuring that food products are culturally appropriate and acceptable. Finally, plant-based analogs may have good market potential in developing countries and could benefit the local food industry, considering that the main raw materials produced in such nations are fruits and vegetables.

4) There is a paucity of studies dealing with sensory determinants of plant-based analogs and consumers' background variables. Exploring further and identifying consumer segments differing in selected demographic, socio-economic, behavioral (i.e., dietary styles) and/or psychographic (i.e., food neophobia) variables would also be relevant to uncovering and overcoming barriers to sustainable eating and drinking solutions.

The outcomes of this review are useful for the food industry to optimize the sensory profile of these innovative food products making them more acceptable to the consumer and competitive on the market.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MA: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft. CC: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft. ML: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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