Research Topics

Food of the future: Meat and dairy alternatives

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Food of the future: Meat and dairy alternatives

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Editorial: Food of the future: meat and dairy alternatives

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Editorial on the Research Topic
Food of the future: meat and dairy alternatives

In recent years, there has been increasing discussion about the impact of our dietary choices not only on our health, but also on global issues such as food security and climate change. Much emphasis has been placed on eating a plant-based diet and avoiding foods of animal origin, with vegetarian options becoming far more abundant across grocery stores and in restaurants. But are we on the right direction? Will meat and dairy alternatives satisfy consumers by living up to their promises? To contribute to this debate, 11 articles have been published in this special issue including 5 on what is called "cultured meat," 4 on plant-based meat/dairy alternatives, and 2 on "hybrid meat" or other alternatives.

In June 2023, the United States became the second country after Singapore to approve the commercialization of "cultured meat" despite uncertainties about this product (1). Failla et al. analyzed 1,151 comments submitted to the 2021 U.S. Department of Agriculture's Food Safety and Inspection Services (USDA-FSIS) call on the labeling of cell-cultured meat. Cultured meat was the preferred labeling term. The majority of comments came from people with unknown affiliation. However, many comments came from farmer advocacy groups and then cell-cultured meat companies. Comments from cell-cultured meat companies and animal welfare associations had the highest median word count. From a recent study, farmers do express complex and nuanced opinions related to food system control and transparency associated with cultured meat as well as potential impacts on the environment, the land, employment, and the life of farming/rural communities (2).

Most investment and research into cultured meat has so far occurred in the US. However, Attwood et al. argued that cultured meat is, so far, an untapped opportunity for the Muslim market thanks to the high projected increase in the world's Muslim population in Asia and Africa. Whether cultured meat can be certified as halal is therefore of paramount importance. Then the potential acceptance of cultured meat by Muslim consumers' needs to be studied in detail, taking into account their specific culture.

In South-Western Europe (Italy, Portugal, and Spain), Liu et al. observed a positive initial attitude toward cultured meat despite fragmented opinions. Indeed, almost two thirds of the respondents were willing to taste cultured meat but only 43% to eat it regularly and 94% would not pay more compared to conventional meat. Younger respondents, scientists or respondents unfamiliar with the meat sector had a higher acceptance. Ethical and environmental concerns were the major motives. Conversely, emotional resistance and lower perceptions of the benefits of cultured meat and of the weaknesses of conventional meat were the main barriers to acceptance of cultured meat.

Using the same survey in 12 African countries (Cameroon, Congo, -DRC Democratic Republic of Congo, Ghana, Ivory Coast, Kenya, Morocco, Nigeria, Senegal South Africa, Tanzania, and Tunisia), Kombolo Ngah et al. confirmed some previous observations, especially the low willingness to pay for cultured meat. Furthermore, people were more likely to try this novel food in the richest and most educated countries surveyed. In addition, a large proportion of respondents strongly agreed that cultured meat would have a negative impact on the rural life confirming other studies conducted using the same protocol but on the French population (3).

Cultured meat is also expected to meet consumers' wishes in terms of sensory and nutritional value, which is not the case yet according to Fraeye et al. (4) and Olenic and Thorrez (1). To et al. analyzed 26 studies directly related to the sensory evaluation of cultured meat. Despite bias due to some potential conflicts of interest for many authors, To et al. attempted to distinguish between what is actually known and all the speculation in order to identify real expectations regarding the sensory characteristics of cultured meat, given the promising narratives of all the proponents.

The lack of standardized terminology for non-animal-based alternatives to animal-based foods has led to the interchangeable use of terms such as meat substitute, replacement, and analog. Addressing this ambiguity, Abbaspour et al. propose a welcome classification. They define "substitute" as a similar product from a culinary perspective, emphasizing functional and sensory properties. "Replacement" refers to options with similar nutritional properties. "Analog" seeks to match both culinary and nutritional attributes, while "alternative" represents a different choice, not necessarily mirroring the original product.

In a broader context, products derived from gene-edited farm animals could also be considered alternatives to conventional animal-based foods. In their study, Martin-Collado et al. explored societal attitudes toward gene-edited meat products. The findings revealed that consumers perceive gene-edited foods akin to genetically modified foods. The authors emphasized the importance of ongoing dialogue to inform consumers about this innovative technology.

Hybrid meat, combining both animal and plant-based proteins, has been observed to face a challenge in consumer acceptance due to limited familiarity (5). In a study by Ryder et al., consumers' verbal associations with hybrid meat improved after a co-creation task, demonstrating positive shifts as familiarity and ingredient knowledge increased. The research underscores a significant obstacle: consumers' lack of understanding regarding the nature and processes involved in developing hybrid meat products.

In their study, Kuosmanen et al. investigated consumers' perceived barriers associated with consumption of selected plant-based alternatives to meat (pulses and meat analogs). The authors employed the Capability, Opportunity, Motivation, Behavior (COM-B) model to interpret the results and observed that the most common perceived barriers for the consumption were unfamiliarity (capability), expensive price (opportunity), and unpleasant taste (motivation).

In addition to meat alternatives, dairy alternatives, such as plant-based milks and yogurts, are actively under study. In the research of D'Andrea et al., the nutritional value of plant-based yogurts was compared to that of dairy yogurts in the US market. The findings revealed that plant-based yogurts contained lower amounts of sugars and sodium, and more fiber, but less protein, calcium, and potassium compared to their dairy counterparts. This study underscores the variability in nutritional profiles between animal-based products and their plant-based alternatives.

McCarron et al. studied oat-based milk alternatives commercially available in the UK. The results indicated that achieving a small particle size is a key target feature, as it correlates with increased lightness, reduced perception of off-white color, and a diminished powdery mouthfeel. Furthermore, the findings suggested avoiding clear (transparent) packaging to prevent off-notes resulting from photo-oxidation. The study emphasizes the importance of sensory analysis in the development of new products.

The articles featured in this Research Topic illustrate that the partial evolution from animal-based to non-animal-based foods not only presents technological challenges but also demands considerations for integrating the alternatives into consumers' diets. Ensuring availability, an acceptable price, and attractive sensory properties are crucial aspects in addition to ethical and environmental benefits. Furthermore, it is essential to address consumer unfamiliarity through objective information based on scientific facts about ingredients, production processes, and nutritional values, as well as offering guidance on preparation. We hope this collection of articles provides insights that inspire further research on the topic.

Author contributions

J-FH: Writing—original draft, Writing—review & editing. SC: Writing—original draft, Writing—review & editing. M-PE-O: Writing—original draft, Writing—review & editing. FF: Writing—original draft, Writing—review & editing. AK: Writing—original draft, Writing—review & editing.

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SC was employed by Isara. FF was employed by IEH Laboratories and Consulting Group.

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Gene-Edited Meat: Disentangling Consumers' Attitudes and Potential Purchase Behavior

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Novel gene-editing (GE) technologies provide promising opportunities to increase livestock productivity and to tackle several global livestock production sustainability and food security challenges. However, these technologies, as with previous genetic modification technologies in food production, are very likely to generate social controversy and opposition toward their use in the meat industry. Here, we explored public attitudes and consumption predisposition toward gene-edited meat products and their potential added benefits to livestock farming. Our results show that societal perception currently comes as a package, where the use of gene-editing technology acts as an extrinsic cue of meat products quality, and is used to make a range of inferences about all quality facets at once. Although consumers with anti-GE attitudinal positions generally were not sensitive to price discounts or added benefits, added benefits increased the consumption predisposition of most moderate and pro-GE consumers, where benefits related to animal welfare had larger effects than those relating to the environment or human health issues.

Keywords: livestock biotechnology, CRISPR, willingness to pay (WTP), added benefits, genetic modification (GM)

IMPLICATIONS

We investigated consumer's attitudes and consumption predisposition toward gene-edited meat products and the potential effect of added benefits to consumption predisposition. We found that people's attitudes are formed toward all genetic engineering technologies without differentiating among them. According to our results, the inclusion of gene-edited meat in the food system will likely face societal opposition, and price discounts would not be an effective strategy to modify consumption predisposition. However, the use of gene-editing technology to reduce the negative impacts of livestock production can influence positively public opinion on the use of the technology in meat production.

INTRODUCTION

Novel gene-editing (GE) technologies offer new opportunities to increase agricultural productivity in the context of a growing human population and to tackle several global agricultural sustainability and food security challenges. These opportunities are particularly promising in livestock industries where the application of other genetic modification (GM) techniques has been relatively limited in scope and scale due to technical and social reasons (1, 2). Unlike previous GM techniques, current development of GE technology is already providing ground-breaking capabilities in livestock industries. Researchers have already generated tools to reduce environmental impacts from livestock production [e.g., increased productivity that leads to reduced environmental impact per unit of output; (3)], improve animal welfare [e.g., increase resistance to foot-and-mouth disease in pigs; (4), or animal dehorning; (5)], reduce risks for human health [e.g., elimination of allergens in eggs; (6)], and improve meat production composition and quality (7). As a relatively new technology, the potential of GE to further provide tools to tackle global livestock industry challenges is large. For example, there are already promising GE solutions to increase resistance to two diseases with a significant economic impact: tuberculosis in cows and porcine reproductive and respiratory syndrome in swine (7–9). To unlock the full potential of this technology would significantly improve the livestock industry's capacity to tackle important challenges of livestock production, in the context of a growing human population and increasing societal demands for environmental, animal welfare, human health and food quality improvements.

Some of these societal demands have and will very likely continue to generate controversy and opposition toward the application of GM and GE technologies in the food industry that go beyond the economic and technical issues (10). These controversies will very likely challenge the full deployment of GE technology in livestock industries, despite its promising potential benefits, as they have done before. Previous GM techniques, and especially transgenic technologies applied to plants (11, 12), faced strong opposition, especially in Europe, which, although this has weakened over time, is still significant (13, 14). Society's perceived risk of genetically modified food relates to unknown or unintended impact of human health, animal welfare and environment (15). Bartkowski and Baum (16) singled out three main factors driving societal concerns toward transgenic technologies, which are usually extrapolated by consumers toward all GM techniques: (a) the lack of precision in GM techniques which leads to doubts about undesirable side-effects, (b) the introduction of foreign DNA to the target species from other species or another variety of the same species (trans- and cis- genic, respectively), and (c) that GM technology has been developed and sold by multinational companies and used mainly in intensive crops and is oriented to the use of herbicides. Unlike traditional GM, GE technology does not introduce foreign DNA but, rather, allows the genome to be edited to exhibit desirable traits naturally expressed in other animals of the same (or closely related) species (17). This key difference removes the foundation of the three above-mentioned social concerns.

Literature relating to differential attitudes toward GM and GE technologies are often contradictory, and therefore need further investigation. Some authors have found in foods from plant origin (i.e., rice) that consumers valued gene-edited (i.e., CRISPR) and genetically modified food similarly, and significantly less than conventional food (18). However, other studies show that consumers are able to differentiate between GM technologies and have different attitudes toward them (19–21).

Attitudes toward traditional GM technologies in food production have been widely studied and found to be variable across time and cultures and influenced by several factors [e.g., (22)]. Consumer acceptance of genetically modified food is largely determined by perceived risk and perceived benefits (23). Novel foods in general, and genetically modified products in particular, are generally more acceptable if they provide tangible benefits for the consumer (23, 24). Knowledge and perceived knowledge on GM technologies are generally a key attitudinal driver, possibly by modulating the perceived risk of using the technologies (22). In this sense, Fernbach et al. (25) found that those people with the most negative view toward GM technologies are generally the least informed, though they believe themselves to be well informed. It has long been known that attitudes toward new technologies and GM use in food production vary in relation to the organism involved (animals, plants, microorganism) (23). Therefore, it is highly likely that societal attitudes toward GE food products of animal origin differ to those toward foods of plants origin. This is possibly because use of GE technology in livestock raises ethical issues that do not apply to crops, such as animal integrity and animal welfare, among others (26–28).

Given this social context, it has been argued that, like traditional genetically modified foods, the largest barrier to a widespread use of GE in the food system is not technical, but is in gaining wide-spread public acceptance and understanding (18). Therefore, in order to maximize the potential positive impact of GE technology in livestock production, it is important to understand public attitudes toward gene-edited meat products. However, there are only a few studies that have analyzed social perceptions of GE in livestock and these focus on very specific uses of the technology [i.e., Polled cattle, (29); GE alternative to castration in pigs, (30)]. This study takes a broader approach which complements the specific findings of the above two studies and other studies focusing on gene-edited plant-origin foods [i.e., (18, 31)]. As such, it aims to enhance the understanding of societal attitudes toward meat products from gene-edited livestock in general, and in relation to potential added benefits to livestock farming. Firstly, we assessed societal attitudes toward gene-edited meat products in the context of wider attitudes toward genetically modified food. Secondly, we analyzed consumption preferences based on consumer willingness to pay (WTP) for gene-edited meat products and how this WTP is affected by attitudes and by product benefits related to key societal concerns about to livestock production. Socioeconomic drivers and real and perceived knowledge of both attitudes and consumption preferences were considered. Ultimately, this study provides information to better understand the societal barriers to the adoption and uptake of GE solutions for global food production challenges.

MATERIALS AND METHODS

Questionnaire Design and Survey Implementation

We developed a questionnaire that consisted of four sections: respondent profile, real and perceived knowledge of GE and GM technologies in food production, attitude toward GE and GM technologies in food production, and WTP for GE meat compared to standard meat. A compromise had to be reached between thoroughness, simplicity, and length. The questionnaire was anonymous, to guarantee a higher level of participation and honesty. Personal data were not required, and there was no financial compensation. Participants were clearly informed of the aim of the study and gave implicit consent for the use of their supplied information in the research according to European regulations. The questionnaire was distributed through an online survey developed using Online Survey platform (https://www.onlinesurveys.ac.uk/). United Kingdom (UK) citizens ($n = 848$) were recruited via Paid Facebook advertising (for 8 days) and the social media accounts of the Roslin Institute and the University of Edinburgh. This study was conducted according to the Declaration of Helsinki for studies on human subjects. The questionnaire was approved by the University of Edinburgh Human Ethical Research Committee (HERC).

The respondent profile section of the questionnaire included questions on gender, age, highest level of education achieved, living environment (either rural or urban), being vegetarian or not, and relationship with farming activity (either being a farmer, having a close family member being a farmer, or no relation). To evaluate real and perceived knowledge of GE technology, respondents were first asked how much they know about GE technology or how it can be used in food production. Possible answers were: "nothing," "a little," or "a lot." Then, those who claimed to know either "a little" or "a lot" were asked a follow up question, where they had to choose the definition of GE technology from three options, only one of which was correct. Respondents were given the following five options:

1. "Taking selected genes from one species of animal or plant, and inserting those genes into a different species of animal or plant" (incorrect)
2. "Taking selected genes from an animal or plant, and inserting those genes into another animal or plant of the same species" (correct)
3. "Altering the DNA of an animal or plant using chemicals or targeted radiation to affect selected genes" (incorrect)
4. "None of the above" (incorrect)
5. "Not sure"

After this section, respondents were provided with the following succinct description of GM and GE technology, in order to ensure that they understood the difference between the technologies:

- "Transgenic food: A plant or animal which has had a useful gene transferred from a different species. For example, a cow with a gene transferred from a fish."
- "Gene-edited food: A plant or animal which has had some of its genes deleted or replaced by genes from another plant or animal of the same species. For example, replacing a gene in a large cow with a gene from a small cow."

The section on attitudes used Likert-type questions using a 7-point scale ranging from "Strongly disagree" to "Strongly agree", with the midpoint being "Neutral." Respondents were asked to state their level of agreement with six statements related to general attitudes toward GM and GE and specific attitude toward ethical, human-health, and environmental aspects of GE, and to the difference between using GE in animals and plants.

Finally, the questionnaire evaluated respondents' WTP for gene-edited meat products compared to "normal" meat. In this exercise, respondents were asked to select which product they would be more likely to purchase (there is an option for no preference) between "normal" chicken breast at a constant price of £6/ kg and gene-edited chicken breast at variable price levels in an iterative process or "bidding game". We used chicken breast because poultry it is the most widely consumer meat in the UK (32). The bidding game started with both products (i.e., gene-edited and "normal") at the same price of £6/kg. If respondent chose gene-edited meat or had "no preference" then the bidding exercise ended. If respondent chose "normal" meat, then the question was repeated again with the gene-edited meat at £5/kg (i.e., £1/kg cheaper than "normal" meat). Questions continued until gene-edited meat was priced at £2/kg (i.e., £4/kg cheaper than "normal" meat). If in that final question respondent still chose "normal" meat, they were considered to not consume GE meat under any price scenario.

This exercise was repeated for gene-edited meat with added benefits to evaluate how purchasing behavior change when improvements in animal welfare, environmental impact, and human health are achieved using GE technologies. Specifically, the following three added-benefit scenarios were tested:

1. Added environmental benefits through breeding chickens that have a lower carbon footprint than non-gene-edited chickens.
2. Added human health benefits through breeding of chickens that produce higher levels of Omega 3 than non-gene-edited chickens.
3. Added animal welfare benefits through breeding chickens that are more resistant to certain diseases than non-gene-edited chickens.

In each scenario, the bidding game started with the gene-edited product at £7/kg, this is £1/kg more expensive than the "normal" product option.

Data Analysis

We used factor and cluster analyses to explore the relationships between attitudes toward different aspects of GE technologies (i.e., ethical, environmental and animal welfare) and to determine if attitudinal groups of individuals could be found. Firstly, we implemented exploratory factor analysis to identify the latent relational structure of the attitudinal aspects explored in the Likert-type questions. We used the "psych" and "GPArotation" packages of R software. The number of factors to select was determined using Horn's parallel analysis (33). We applied an Oblimin rotation and ordinary least squared factoring, which does not assume a multivariate normal distribution. Secondly, we used the root mean square of residuals (RMSR) and the Tucker-Lewis Index (TLI) to validate the factor model. Finally, we implemented k-means cluster analysis on the resulting factors to distinguish attitudinal groups across the sample. The number of clusters was determined by the partition with the highest loss of inertia (within cluster sum of squares). Differences in attitudinal group profiles were evaluated using ANOVA test and Bonferroni pairwise *t*-test for quantitative normally distributed variables and Pearson's chi-squared test for categorical variables.

We analyzed the WTP bidding-game results by comparing the proportion of respondents that prefer the gene-edited product over the standard one, at different price discounts in the different added-benefits scenarios. In addition, differences between attitudinal groups were determined according to their average WTP for gene-edited meat with added-benefits. Differences between groups were evaluated using the non-parametric Wilcoxon signed-rank test. Respondents who would not consume gene-edited meat at any price were not included in the WTP calculation.

RESULTS

Attitudes Toward GE Use in Food Production

We found that the latent relational structure of the attitudinal aspects was best described by just one factor. RMSR was 0.05 (should be close to 0) and TLI was 0.987 (should be above 0.9) showing the adequacy of the result. This single factor comprises attitudes toward GM and GE and all human-health, environment, and animal welfare components of GE (**Table 1**). We call this factor the "Attitude toward GE & GM factor" herein. The statement relating to differential treatment of animals and plants regarding GE is not part of this factor, meaning that this particular attitude is independent of respondents' attitude toward GE and GM.

We ran the cluster analysis on two variables: the Attitude toward GE & GM factor and the (typified) variable corresponding to the attitudinal statement related to differential treatment of plants and animals (last statement in **Table 1**). The cluster analysis determined the existence of the following four groups of respondents (**Table 2**):

1. Anti-GE, Kingdom indifferent (18.9% of respondents): Respondents in this group had a very negative attitude toward GE and GM in food production, and consistently consider that animal and plant kingdoms should be treated in the same way when using GE for food production. Since this group made no distinction between animal and plant kingdoms, we called it Kingdom indifferent.
2. Anti-GE, Kingdom different (27.6%): Respondents in this group have a negative attitude toward GE and GM, but contrary to the previous group, they strongly believe that plant and animal kingdoms should be treated differently for GE in food production.
3. Moderate (42.1%): It is the largest group of respondents in the sample. They have neutral or slightly positive attitudes toward GE and GM in food production and consider that animals and plants should be treated differently.
4. Pro-GE (11.4%): This is the smallest attitudinal group in the sample. This group has very positive attitudes toward GE and GM, and strongly considers that plants and animals should not be treated differently.

A more detailed description of the distribution of the attitudinal positions regarding GE in each group is presented in **Figure 1**.

Socioeconomic Drivers of Attitudes

We found that attitudinal groups have different demographic profiles (**Table 3**). Groups with a more positive attitude toward GE and GM are associated with youth, being male, consuming meat, and living in an urban environment. There were no clear differences between attitudinal groups regarding education level, employment situation, or relationship with farming ($P > 0.05$).

Respondents that claimed to have no knowledge of GE had a less favorable attitudes toward GE & GM than respondents that declared some knowledge (either "a little" or "a lot"; **Table 4**), however, there was no (statistical) differences in attitude between those who believed to know "a lot" about GE and those who claimed to know "a little". On the contrary, real knowledge about GE technology had no influence on attitudes. There were no statistical differences in the weight of the Attitude toward GE & GM factor between respondents who got the correct definition of GE technology, respondents who got it wrong, and respondents who were unsure about it. Furthermore, 57.1% of the people that claimed to know "a little" about GE technology and 78.8% of the people that claimed to know "a lot" were not able to select its correct definition. Note that real knowledge was only determined for respondents claiming to have some knowledge of GE, either "a little" or "a lot".

Willingness to Pay for Gene-Edited Meat Products

Figure 2 and **Table 5** illustrate the results of the WTP exercise. Almost half (47.1%) of respondents stated that they would always choose "normal" meat instead of gene-edited meat regardless of the price discount. Adding benefits to gene-edited meat slightly changed this proportion; 40% would always choose normal meat instead of GE meat with improved animal welfare, 41% for lower environmental impacts, and 43.6% for increased human health benefits. On the other side, at equal prices 35% of respondents either prefer gene edited meat (without special features) or have no preference between gene-edited meat or "normal" meat. Finally, 17.9% of the respondents chose gene-edited meat when price discounts were offered. When respondents were asked to consider gene-edited meat in the context of additional benefits associated with GE technology, a large proportion of respondent would pay a premium of £1/kg (41.3% for improved animal

TABLE 1 | Composition of the gene-editing (GE) attitudinal factor.

Attitudinal statement	Factor 1	h2
I have a positive perception toward genetically modified foods	0.90	0.82
I would be comfortable eating food produced using GE technology	0.95	0.90
GE in food production is ethical	0.92	0.85
GE in food production is safe for human health	0.95	0.90
GE in food production is safe for the environment	0.93	0.87
GE in animals and plants used for food production should be treated differently	−0.08	0.01
Proportion of variance explained	0.72	

Standardized loading of attitudinal statements.

TABLE 2 | Description of attitudinal groups according to the variables used in the cluster analysis.

Attitudinal group	*n*	[a]Attitude toward gene-editing and genetic modification (factor)	Attitude toward differential treatment of animals and plants in gene-editing (typified variable)
Anti-gene-editing, Kingdom indifferent	160	$-0.98^{A} \pm 0.37$	$-1.35^{A} \pm 0.34$
Anti-gene-editing , Kingdom different	234	$-0.81^{B} \pm 0.39$	$0.87^{D} \pm 0.54$
Moderate	357	$0.57^{C} \pm 0.5$	$0.29^{C} \pm 0.47$
Pro gene-editing	97	$1.31^{D} \pm 0.39$	$-1.05^{B} \pm 0.4$
Total	848	0.0 ± 1.0	0.0 ± 1.0

[a]*Negative values refer to negative attitudes toward gene-editing and genetic modification and that animals and plants should be treated in the same way. All consumer groups showed significant differences for the attitudinal factors according to ANOVA tests ($P > 0.001$).*
[A–D] *Different letters indicate statistically significant differences between consumer groups according to Bonferroni pairwise t-test ($P < 0.001$).*

welfare, 34.0% for lower environmental impact, and 31.8% for increased human health benefits).

Attitudinal groups clearly differentiated in their WTP for gene-edited meat and consumption predisposition (**Table 5**). On the one hand, "Anti-GE" groups had a lower WTP for gene-edited meat than the "Moderate" and the "Pro-GE" groups. Average WTP is negative in all groups but in "Pro-GE", (which is very close to 0), meaning that price discounts were required for them to purchase the gene-edited meat. Furthermore, most people in "Anti-GE" groups (91.5 and 96.5% in "Kingdom indifferent" and "Kingdom different" groups, respectively) stated that they would not consume gene-edited meat regardless of the price discount and the associated benefits (**Figure 3**).

Influence of Additional Benefits on WTP for Gene-Edited Meat Products

When considering gene-edited meat with additional benefits, WTP increased in all attitudinal groups; "Anti-GE" groups still showed a negative WTP, but both "Moderate" and "Pro-GE" groups showed a positive WTP (**Table 5**). Across all attitudinal groups, WTP was highest when benefits were associated with improving animal welfare (increasing animal disease resistance) and lowest when benefits were associated with human health (increased Omega 3 levels).

Finally, we found that some respondents that previously stated they would not eat standard gene-edited meat regardless of the price discount changed their mind when benefits were introduced (**Figure 3**). The proportion of respondents that changed their mind varied across attitudinal groups. Close to half of the "Moderate" group (40%) changed their mind, but only a small proportion of "Anti–GE, Kingdom different" (11.5%) and "Anti–GE, Kingdom indifferent" (4.3%) groups would do so. Again, across all attitudinal groups, benefits associated with animal welfare and lowering GHG emissions where more important than benefits for human health.

DISCUSSION

Societal opposition to GM use for food production has limited its adoption in agriculture, especially in European countries. Although nowadays there is less societal debate about GM technology than a decade ago, a large part of the society is still concerned about it use in the food industry [e.g., (13, 14)]. This historic debate focused on GM crops because its application to livestock production was very limited. Because new GE technology developments have been successfully applied in livestock [e.g., (4–7)], there is a renewed interest in analyzing the people's specific attitudes toward its use in meat production. However, only a few studies have analyzed societal attitudes toward specific uses of GE technology in livestock production. To our knowledge, this study is the first to analyse general consumers' attitudes toward GE technology in livestock production and WTP for gene-edited meat products with and without potential animal welfare, environmental, and human health benefits.

The results of our investigation add to a growing body of research which suggests that society will view gene-edited foods similarly to how they view genetically modified foods (18, 22),

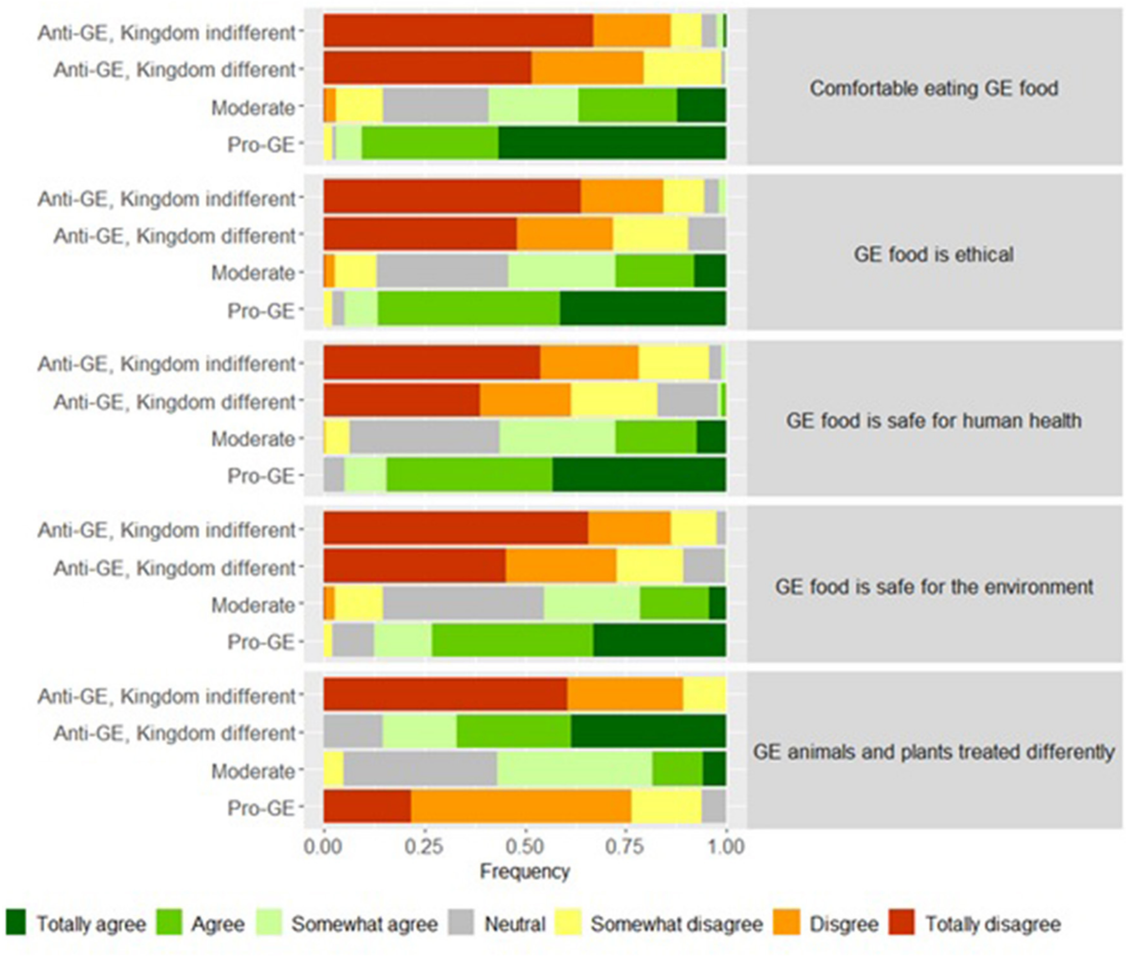

FIGURE 1 | Attitude toward different aspect related to gene-editing (GE) in food production across attitudinal groups.

which implies that inclusion in the food system would be controversial. We found similar attitudinal groups and drivers of attitudes and consumption predisposition (i.e., age, gender, place of living and perceived knowledge) than previous studies. Our results also show that attitudes are likely to be positively affected by added benefits. Finally, unlike the use of GE in crops, gene-edited meat raises issues related to animal welfare, which affects both the intrinsic components of attitudes toward GE, and people's evaluation of potential benefits of this technology. These issues are discussed in detail below.

Attitudinal Dimensions

According to our study, attitudes toward gene-edited meat products are built on two independent attitudinal dimensions: the attitude toward GM and GE technologies in food production, and the attitude toward the differential treatment of animals and plants. Attitudes (either positive or negative) toward the use of GE technology for food production are consistently created toward the "whole package" of GE and all its facets related to ethical aspects, human health, and environmental issues, without distinguishing between them, along with genetically modified foods in general. This result shows that GE possibly functions as an extrinsic cue (i.e., signal) of food product quality (34), similarly to how meat origin, and animal feed or production system can signal food product quality (35). In this sense, GE would work as a consumer heuristic that backs up a story of the production process, which is used by people to make a whole range of inferences about product quality, leaving no space for nuance.

Attitudinal Groups

The combination of both attitudinal dimensions in a factor analysis allowed us to identify four attitudinal groups of people; two anti-GE, one moderate, and one pro-GE. The opinion on the differential treatment of animals and plants was key to segmenting attitudinal positions, with the most extremely pro-GE attitudinal groups not differentiating between animals and plants under any circumstance. The two anti-GE groups differentiated in their position toward treating animal and plants differently. The existence of anti ("pessimistic"),

TABLE 3 | Description of attitudinal groups; age, and proportion of females, vegetarians, and urban dwellers.

Attitudinal group	*n*	Mean age	Females (%)	Vegetarians (%)	Urban (%)
Anti-gene-editing, Kingdom indifferent	160	$57.4^{A} \pm 12.2$	74.5%	21.9%	49.4%
Anti-gene-editing, Kingdom different	234	$56.9^{A} \pm 14.1$	82.5%	28.2%	56.0%
Moderate	357	$50.5^{B} \pm 18.2$	72.0%	14.0%	63.9%
Pro- gene-editing	97	$43.1^{C} \pm 17.4$	49.5%	9.3%	69.1%
Total	848	47.6	68%	19%	61%
ANOVA test *p*-value		$P < 0.001$			
Chi^2 *p*-value			$P < 0.001$	$P < 0.001$	$P < 0.001$

A–D Different letters indicate statistically significant differences between attitudinal groups, calculated according to Bonferroni pairwise t-test (P < 0.001).

TABLE 4 | Relation between attitude and perceived and real knowledge toward gene-editing technology.

	Number of respondents (%)	Attitude toward gene-editing and genetic modification factor (average and SD)
Perceived knowledge of gene-editing technology		
None	287 (28.5%)	$-0.19^{A} \pm 0.77$
A little	439 (51.4%)	$0.00^{B} \pm 0.94$
A lot	122 (20.1%)	$0.33^{B} \pm 1.19$
[a]**Real knowledge; respondents guessing right the true definition of gene-editing technology**		
Correct	157 (27.8%)	0.14 ± 0.96
Incorrect	345 (61.1%)	0.09 ± 1.04
Not sure	63 (11%)	-0.17 ± 0.92

[a] Real knowledge was only determined for respondent declaring to have some knowledge on gene-editing, either "a little" or "a lot".
A–D Different letters indicate statistically significant differences between groups by perceived knowledge, calculated according to Bonferroni pairwise t-test (P < 0.001).

moderates ("undecided"), and pro ("optimistic") groups have been consistently found by several authors when studying people perception on genetically modified food [e.g., (22)]. Unlike most of these studies which found that the "optimistic" group was usually rather large, our results show that when it comes to GE meat products, negative and moderate attitudinal positions dominate public opinion, with only a small proportion of respondent having pro-GE attitudes beyond doubt. The greater reluctance to use GE in livestock compared to using it in plants is very likely related to the great public concern for farm animal welfare (36, 37). Note that most respondents in our study consider that plant and animals are not the same and therefore should be treated differently in regard with GE.

Attitudinal Drivers

Our study shows that youth and gender (i.e., males), and to a lesser extent place of living (i.e., urban), and non-vegetarianism, influenced positively attitudes toward GE use in meat production. These results are in line with previous studies which found that age and gender generally influence attitudes toward using GM technology in food production [e.g., (22, 38, 39)] and livestock welfare issues [e.g., (40–42)]. Similarly, urban inhabitants are usually found to have a more positive attitude toward GM use in food production [e.g., (43, 44)].

Perceived knowledge on genetically modified food has been widely studied, and is usually separated between real (tested) knowledge and perceived (self-assessed) knowledge. In accordance with House et al. (45), we found that the lower the perceived knowledge of the respondent on GE technology the more negative the attitude toward it (and the lower WTP for GE meat products). Low knowledge increases risk perception, which has been proven to be strongly related to GM acceptability (22, 46). Contrary to other authors [e.g., (22, 45, 47)], we found no relationship between real knowledge and attitudes or WTP, however, these differences may be due to differences in the way "knowledge" is measured across studies (45).

Consumption Predisposition, WTP and Perceived Benefits

The WTP exercise showed that respondent predisposition to consume gene-edited meat products is negative (i.e., price discounts are generally required) and is not influenced by further price discounts in large share of the respondents. Almost half of respondents would not consume gene-edited meat products regardless of the price, while around one third of the sample would have no problem consuming it. This means that only a small proportion of respondents (around 15%) were shown to be sensitive to price discounts. As expected, WTP from gene-edited meat products is very much related to attitudes toward it, with Anti-GE groups showing a much lower (negative) average WTP and a lower sensitivity to price discounts than Moderate and Pro-GE groups.

It is widely known that the use of GM to get added benefits increases consumers' acceptability and WTP for genetically modified products [e.g., (23, 24, 48)]. This has proved to also hold true for specific examples of GE technology use for increasing

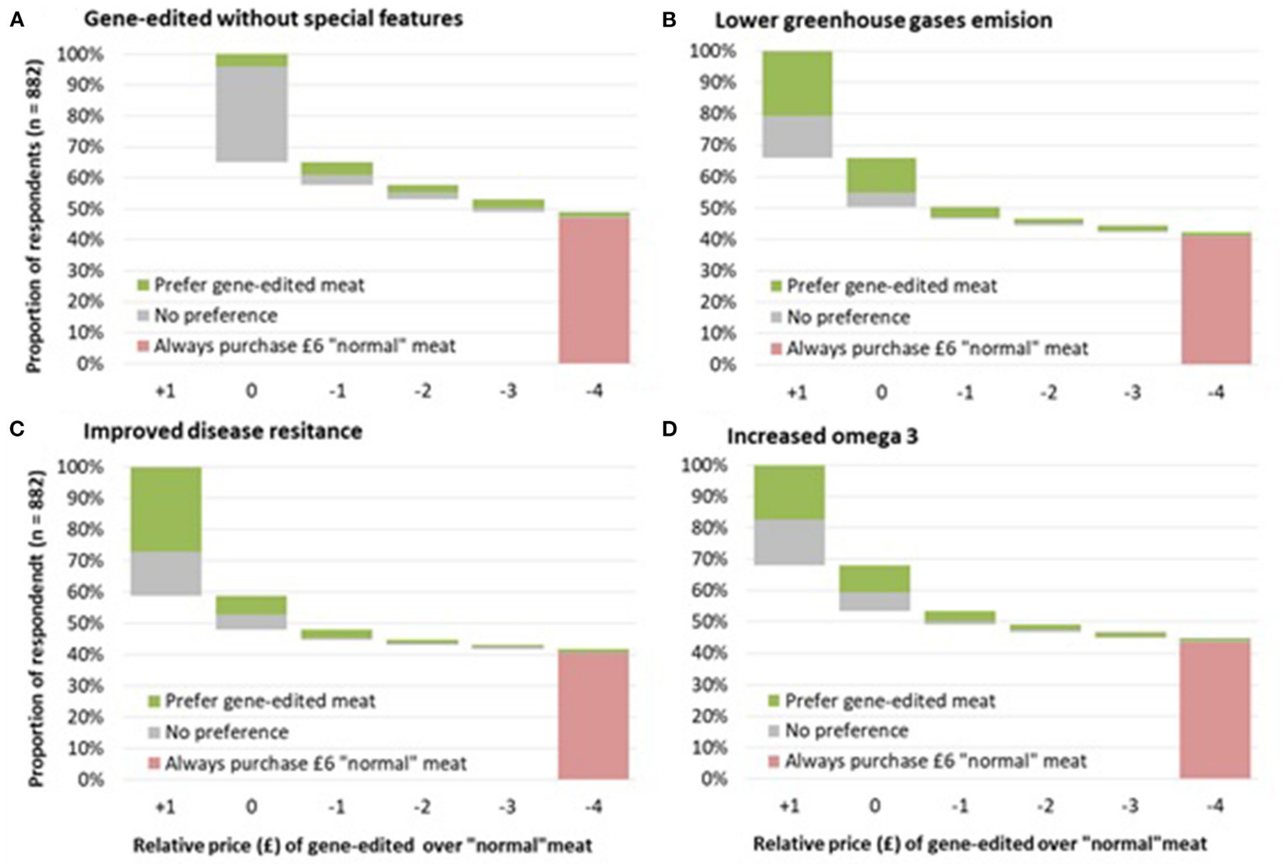

FIGURE 2 | Willingness to pay for gene-edited meat (chicken breast) by its relative price compared to normal meat (£6/kg.).

animal welfare in livestock production; i.e., polled cattle (29) and alternative to castration in pigs (30). We indeed found, in a more general approach, that added benefits increased WTP for gene-edited meat products and that the effect was larger on benefits related to animal welfare, than to environmental or human health issues. This finding fits with the high relative importance that western society gives to animal rights within livestock production, and the higher importance of animal welfare compared to other livestock challenges [e.g., (29, 38)]. However, our study also shows that the respondent attitudes are affected by added benefits to a limited extent and differently across attitudinal groups. Most of the people who hold Anti-GE positions would not consume gene-edited meat products regardless of the price discount and they would not modify their consumption predisposition when either animal welfare, environmental or human health benefits are added. On the contrary, most Moderates and Pro-GE respondents attitudes are sensitive to added benefits. Actually, Moderates and Pro-GEs people, who on average would require price discounts to consume gene-edited meat products, would on average be willing to pay overprice (0.27–0.73£/Kg depending on the type of benefit) for gene-edited meat with added benefits. Our research suggests that GE technology use in meat production would initially be acceptable to around half of consumers, although most of them would require a price discount or added-benefits to prefer gene-edited meat over normal meat.

Limitations

This study has a number of limitations that should be acknowledged. Firstly, participants were recruited via online advertising, which, although provides a practical, cost-effective, and efficient way to gather a large and diverse sample, might bias the sampling toward internet users. Given the large usage of internet in UK households (90% of homes, 2020), we do not expect a large bias in this regard. We should also note that our sample might be slightly biased toward anti-GE positions as social groups that showed more negative attitudes toward GE use in meat production (rural, females, and aged) were to some extent overrepresented in the sample compared to overall UK population [(49); **Supplementary Table 1**]. Therefore, care is required when making inferences of the results of the survey about the whole UK population.

Similarly, our study was focused on the UK so its results cannot be immediately extrapolated to other countries. Previous studies on attitudes toward GM and GE food

TABLE 5 | Willingness to pay for gene-edited meat with different beneficial features across attitudinal groups.

[1]Willingness to pay (£) for gene-edited meat products	Attitudinal group				
	Anti-gene-editing, Kingdom indifferent (n = 125)	Anti-gene-editing, Kingdom different (n = 168)	Moderate (n = 307)	Pro-gene-editing (n = 88)	All (n = 688)
Without special features	$-2.10^{ab} \pm 1.6$	$-2.05^{a} \pm 1.28$	$-0.72^{b} \pm 1.13$	$-0.14^{c} \pm 0.46$	-0.69 ± 1.14
From animal with increased disease resistance	$-0.87^{a} \pm 2.17$	$-0.19^{ab} \pm 1.63$	$0.49^{ab} \pm 0.99$	$0.73^{b} \pm 0.6$	0.43 ± 1.11
From animal with lowered GHG emission	$-1.08^{ab} \pm 1.94$	$-0.89^{a} \pm 1.81$	$0.35^{bc} \pm 1.03$	$0.59^{c} \pm 0.62$	0.25 ± 1.18
With increased Omega3 content	$-1.0^{abc} \pm 2.16$	$-0.72^{a} \pm 1.69$	$0.27^{b} \pm 1.1$	$0.54^{c} \pm 0.69$	0.22 ± 1.19

[1]*Average and SD willingness to pay among those respondents willing to consume gene-edited meat. Negative values refer to discount required by consumers in order to purchase.*
[a–c] *Different letters indicate statistically significant differences between consumer groups, calculated according to Pairwise t-test variance ($P < 0.05$).*

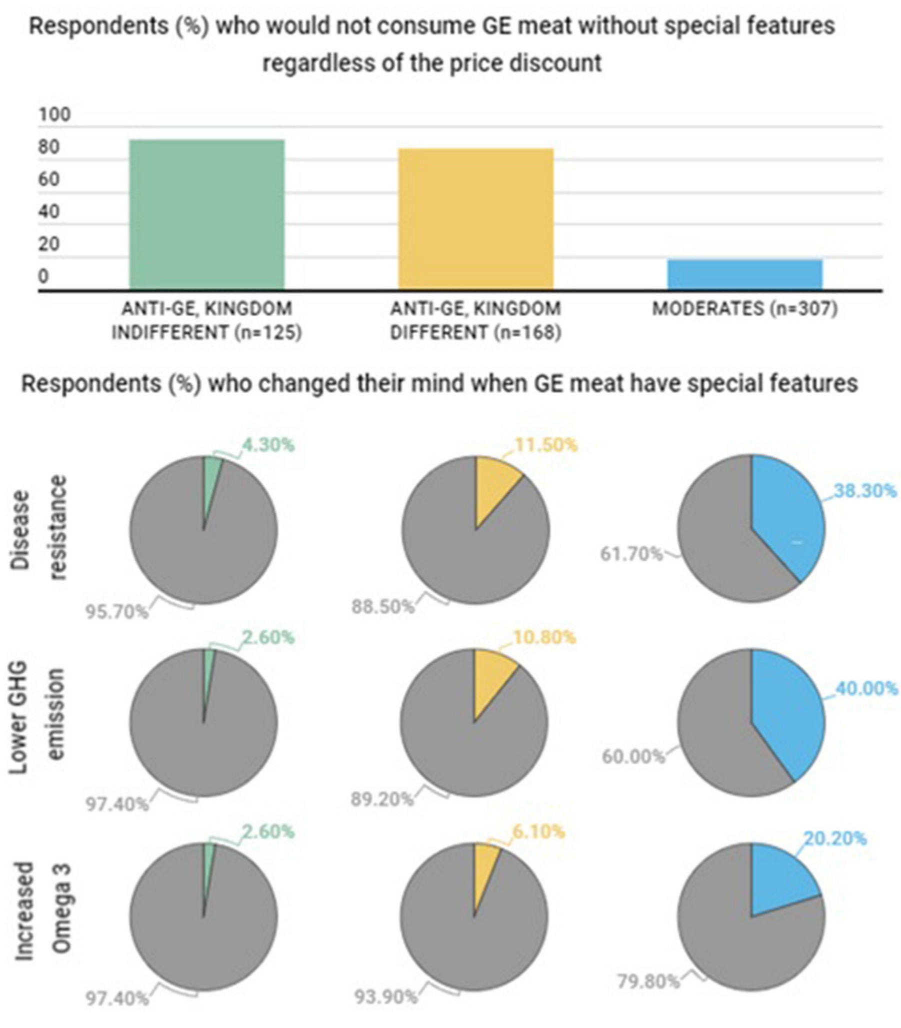

FIGURE 3 | Influence of added benefits in gene-edited (GE) meat consumption across attitudinal groups.

products across regions and countries [e.g., (18)], generally found similar attitudinal behaviors across western countries, with European citizens being the ones showing the greatest concern. Therefore, the results of our study only apply to UK. However, given the similarity of UK society with other European societies, with regard to attitudes toward

GM and GE technology uses in food production, we would not expect results in other European countries to be very different. Extrapolation out of Europe should be done with care.

We should also note that attitudes that consumers express toward food products are not (always) strongly related to purchase behavior. However, this does not necessarily mean that attitude does not affect other behaviors, for example political behavior (34). Therefore, we should not interpret the implications of the results of our study only in terms of its impact people's role as consumers, but also in terms of potential influence on people's role as citizens. Currently, livestock production and meat consumption are important issues politically [e.g., (26, 50)]. Therefore, negative attitudes toward gene-edited meat found in our study might not (only) have a large effect on the future consumption of potential products, but are also likely to have a strong influence on public opinion and in turn in policy and regulatory decisions.

Finally, gene editing technology is still a largely unknown among the general public, which presumably will change as the technology develops and its adoption in the farming sector spreads. Since people's attitudes are largely influenced by their knowledge, as discussed above, it is possible that that the attitudes reflected in this study change soon, particularly given the interest of GE technology developers in making society distinguish between this technology and traditional GM.

Implications for GE Technologies Development

As GE technologies continue to advance, society must make decisions about their role in the food system. There are two clear messages emerging from our study. First, that perception of these technologies currently comes as a package; individuals start from either a supportive or a concerned stance for all genetic engineering technology. Our results add to a growing body of research which suggests that society will view gene-edited foods similarly to how they view genetically modified foods. The second conclusion is that there is a need for continued dialogue to provide the information that individuals seek. There remains an opportunity to differentiate people's perceptions between GE and GM, while our data strongly supports the need to communicate the benefits the technology offers to society. If there are real differences in the application and benefits of the different genetic engineering technologies, then these need to be better articulated to enable society to develop informed opinions. Consumer decisions on whether or not to buy GE food is not fixed, and changes in opinion remain possible. Changes will be reliant on clear, transparent dialogue around the benefits that the technology can deliver to society. The ability to appropriately communicate the improvements of GE technology over previous GM techniques on issues of high importance to society, like meat quality, environmental impact and animal welfare, will likely shape the evolution of public attitudes toward it use in meat production, and in turn affect how the sector develops. In parallel, fair societal concerns around the ethics of artificially modifying animals' genomes remain, and these will continue to influence this dialogue. All actors have a role to play in the dialogue, from transparent representation by industry, to informed decision making by stakeholders, with trusted information sources likely to reside in recognized academic institutions. More research is needed to investigate the relationship between attitudes toward GE technologies and different messaging and communication strategies, and how consumers respond to labels highlighting different information or positive benefits associated with GE technology.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

DM-C: methodology, formal analysis, writing—original draft, writing—review and editing, and visualization. TB: conceptualization, methodology, investigation, resources, writing—review and editing, supervision, and project administration. JC: methodology, formal analysis, investigation, writing—review and editing, and visualization. TK: conceptualization, methodology, formal analysis, investigation, writing—review and editing, and visualization. GR: writing—review and editing. CW: conceptualization, resources, writing—review and editing, supervision, and funding acquisition. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2022.856491/full#supplementary-material

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Hybrid meat products and co-creation: What do consumers say, feel and think?

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Introduction: What consumers say about food and what kind of words they use to do so offers direct insights into their perceptions, preferences, reasoning, and emotions.

Methods: This study explores evaluations of hybrid meat products of 2,405 consumers from England, Denmark, and Spain. As part of a large survey, consumers were prompted to note down four words that come to mind when they read a description of a hybrid meat product, and then again after they were involved in a hypothetical co-creation task of a hybrid meat product. 18,697 words and phrases of language material was processed using computational corpus-based analysis and manual classification into semantic categories including: Evaluation, Sensory, Production, Emotion, Diets, Quality, Ethics, and Other.

Results: Consumers consider many dimensions when it comes to the evaluation of hybrid meat products including ethical conduct and sustainability. For all three languages, the number of positive words increased and the number of negative words decreased significantly ($p < 0.001$) following the co-creation task, suggesting that consumers see such products very positively once they are more familiar with them and know more about the ingredients. Subcategories that received most words include: taste, ingredients, healthiness, naturalness, innovation, and environment, implying that these areas are of most importance when it comes to the evaluation of hybrid meat products. The concept of nutrition (especially words pointing to positive aspects such as "rich in vitamins", "nutritious") also rose significantly in use after co-creation.

Discussion: The study reveals consumers' vocabulary of hybrid meat products across the three countries and offers important insights for food producers to help them create innovative products that better align with consumers' perceptions and expectations.

KEYWORDS

consumer co-creation, word associations, evaluation, hybrid meat products, cross-cultural, United Kingdom, Spain, Denmark

1. Introduction

Flexitarian eating has been on the rise in recent years and seems to have accelerated post the Covid-19 pandemic and in younger populations referred to as Gen Z. According to the recent YouGov data, one in five 18-to-24-year-olds currently follow such a diet and the number has doubled since 2019 (1). Flexitarian diet includes both: reducing meat consumption and meat portion size along the week, and having more plant-based and meat-free meals (2). In this context, a diversity of hybrid meat products have been introduced on the market; these products are specifically designed to blend meat and plant-based ingredients in convenient ready to cook forms, such as burgers, sausages or minced products (3). Despite the novelty of this hybrid concept, some consumer studies have already been carried out (4–6), and recent research has focussed on understanding consumer attitudes toward such products, including consumers' views on their formulation and different types of messaging on them (7, 8).

Since consumers are an essential part in the new product development process and their attitudes and views can increase (or decrease) the likelihood of success of a new product on the market, co-creation has been suggested as a valuable tool to understand consumers' concerns and perceptions, and engage them in the design of new food products (9). For example, consumer co-creation has been recently applied in a cross-country study involving consumers from United Kingdom, Spain, and Denmark, with the aim to understand the preferred ingredients to use in the manufacturing of hybrid meat products (8). A comparison of the consumption habits for processed meat in these three countries, to each other as well as to Europe and worldwide, can be seen in **Table 1**. Note that "Processed Meat" in this sense includes cold and roast meat products, ham and bacon, and sausages; fresh meat and pre-cooked meat-based ready-to-eat products are not included.

In the present study and covering the same countries, we use a linguistic word analysis approach to compare consumer attitudes toward hybrid meat products under two different conditions: the first condition exposed consumers to a written definition of hybrid meat products and the second invited them to a participative co-creation task of hybrid meat products, in which they could build their preferred product in a series of short steps. Following each condition, participants were prompted to provide any four words about the product that came to mind. Subsequently, the words were analysed systematically using frequencies and semantic categorisation.

This kind of free word association analysis is a very powerful tool that can tap into consumers' involuntary, and therefore more authentic preferences, expectations, reasoning and emotions when it comes to evaluating novel food products [e.g., (10–12)]. This is important to understand since most of the consumers' everyday decision making is determined by a constellation of spontaneous experiential, affective, and reasoning factors (13), and words that come to mind spontaneously can reflect these constellations unlike experiments conducted in laboratory settings. What consumers think spontaneously about hybrid meat products can therefore help producers of such products understand why certain products are preferred over others, and therefore more likely to be purchased. Research has shown that the understanding of this kind of free and spontaneous word associations facilitate an effective food product development and can assist with successful introduction of novel of healthy foods [e.g., for a systematic review on this research see (14)]. Furthermore, since co-creation has been shown to increase the likelihood of success of novel food products, word association analysis post a co-creation task can further enhance our understanding of the role of consumer engagement in novel food creation, and provide food manufacturers with relevant information to help them align the development of hybrid meat products with consumers' preferences and expectations. This study therefore aims to explore the following research questions:

1. How do consumers perceive and evaluate hybrid meat products upon first presentation?
2. How do these perceptions change following the co-creation of a hybrid meat product?
3. In what ways does the linguistic and cultural context affect perceptions of hybrid meat products both before and after co-creation?

This study takes an innovative approach to the examination of hybrid meat products, firstly due to its foundations in Grasso et al. (8) pioneering study into the co-creation of hybrid meat products in the United Kingdom, Spain, and Denmark, and secondly by building on the corpus-linguistic approach to investigating perceptions and preferences around this kind of products that was established by Grasso and Jaworska (3) in the study of online reviews of hybrid meat products. In doing so, this study contributes to the growing body of research which utilises a combination of qualitative, projective techniques with quantitative methods to gain a more holistic understanding of consumers' perceptions, preferences and attitudes (14), here specifically in relation to novel hybrid meat products before and after co-creation.

2. Data and methods

Grasso et al. (8) outline the process of participant recruitment for the questionnaire that was put to consumers in the United Kingdom, Spain, and Denmark, including an element in which consumers "co-created" their own hybrid meat product, in order to identify willingness to try (WTT) and willingness to buy (WTB) hybrid meat products in each of these countries. In this questionnaire, consumers were presented with a hybrid meat product and asked to provide four words that came to mind based on their first impression; they were asked to repeat this exercise when presented with the hybrid meat product that they had developed as part of the co-creation task. While studies focussing on general terms often ask participants to note down three words, most research on food and food behaviour that used the word association technique required more words mostly four [e.g., (11, 12)] to account for the diversity of dimensions and aspects that people associate with food and give participants a bit more "space" to report on those. We followed this parameter in this study too and selected four as the number of words to write down.

For the purpose of this study, "word" in the context of a consumer's response refers to any single response from a user regardless of its length; thus, a "word" may be anything from the individual words *healthy*, *gross*, or *awareness* to phrasal responses such as *environmentally-friendly* or *a bit weird*. In some instances, consumers provided longer clausal responses such as *good way to get more vegetables* or *I wouldn't buy it* and those were considered too.

Subsequently, all lexical items were categorised according to their dominant semantic meanings. Seven main categories were identified including: Evaluation, Sensory, Production, Emotion,

TABLE 1 Average volume (kg) per capita for estimated 2023 consumption of processed meat.[a]

Region	Cold and roast meat	Ham and bacon	Sausages	Total
UK	8.2	2.1	2.7	12.9
Spain	4.4	2.7	4.1	11.2
Denmark	7.1	2.6	8.6	18.3
Europe	18.8	7.2	3.2	7.4
Worldwide	2.3	0.8	1.9	5.1

[a]Source: Statista (15).

Diets, Quality, Ethics, and Other. Given the wide range of words and phrases provided by consumers, each main category was then divided into relevant subcategories of meanings. The process of classifying the words and phrases into the categories was conducted iteratively and often by considering the context, that is, the other words that were provided in the response. Because of the explicit nature of the task, the meanings of most words and phrases were unambiguous and easy to categorise. In some ambiguous cases, the Oxford English Dictionary was consulted (16). An interrater was employed to classify 30% of the data with words and phrases from each category and subcategory. The agreement rate was generally high above 85%; any inconsistencies were resolved on the spot, and changes adopted.

A total of 802 participants in each of the United Kingdom and Demark, and 801 in Spain, provided words in English, Spanish, or Danish. Some respondents in Spain and Denmark provided their responses in English; for those who responded in Spanish and Danish, words were translated for the purposes of analysis. Theoretically, the total possible word yield for each language was 3,208 (3,204 for Spanish); however, certain words were rejected from the analysis for one of the following reasons:

- they appeared to be nonsense or gibberish, or were perhaps the result of a typo so severe that the original meaning could not be determined;
- the same word occurred more than once in a single set of four-word responses from a single consumer, i.e., the consumer repeated a word;
- a phrasal/clausal response was spread across more than one field—for example, one user responded with *I*, *don't*, *like*, and *it*, which were amalgamated as the single response *I don't like it*.

The total number of words for each language in each condition—both before (−CC) and after (+CC) the co-creation of a hybrid meat product—is provided in Table 2. Note that clausal responses were significantly ($p < 0.001$) more common in responses from Danish consumers when compared to English and Spanish, accounting for the majority of the variation in number of words for that language since therefore multiple fields were more often amalgamated into one response.

TABLE 2 Words provided by participants in each language before and after co-creation of a hybrid meat product.

	English $n = 802$	Spanish $n = 801$	Danish $n = 802$
−CC	3,151	3,168	3,022
+CC	3,153	3,177	3,026

Throughout the analysis that follows, statistical significance was determined through treatment of the figures above as six individual corpora and a calculation of the log-likelihood value. This standard measure of statistical significance in corpus linguistics takes the frequency of a particular phenomenon in one corpus or "body" of words and compares it to another, relative to the total size of each corpus; the log-likelihood is therefore a probability statistic that measures the likelihood of frequency differences between two or more corpora as occurring due to chance. This is then compared to a table of critical values to determine the statistical significance—or lack thereof—of the difference in frequency between the corpora. More information on the use of statistical analyses in corpus linguistics can be found in McEnery and Hardie (17).

3. Perceptions and evaluations of hybrid meat products

Following the process of classifying the words in accordance with their meanings, the following main semantic categories (with subcategories) emerged: Evaluation, Sensory, Production, Emotion, Diets, Quality, Ethics and Other. The full set of categories is provided in Table 3, with examples for each. As Table 3 shows, consumers referred to a range of dimensions when prompted to provide four words about hybrid-meat products before (−CC) and after (+CC) co-creation. While categories such as Sensory or general Evaluation are expected, there also other aspects that were deemed relevant by consumers such as Ethics and varied dimensions of Quality and Emotion. This suggests that, when it comes to new hybrid food products, consumers do not just focus on one aspect—for example, only the sensory experience—but consider a variety of issues related to food production and consumption, including ethical conduct and sustainability, that are not often clearly communicated by food manufacturers.

Some interesting differences can be observed regarding the responses provided by the three national groups of consumers. Whereas, and as expected, Evaluation was relevant for all, words pointing to Emotion and Ethics were more often employed by Danish respondents, especially before the co-creation task, but this also remained quite relevant after the co-creation task. This suggests that Danish consumers might place more value on ethical and sustainable food production and consumption, and tend to express their preferences in a more emotional way. In addition, dimensions involved in Production of the hybrid meat products

TABLE 3 Frequency of consumer responses by category both before and after co-creation for each language.

Semantic category	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Evaluation	3,151	3,153	3,168	3,177	3,022	3,026
Sensory	644	806	425	707	454	626
Production	320	361	451	471	406	440
Emotion	305	308	333	280	444	387
Diets	174	27	211	41	113	18
Quality	1,006	1,030	1,217	1,148	900	881
Ethics	217	151	254	189	347	262
Other	219	161	131	109	144	153

(including ingredients and nutritional value) seem to be more important for Spanish and Danish respondents than those from the United Kingdom.

In the sections that follow, each of the categories listed in Table 4 is taken in turn and noteworthy observations are made about some or all of the subcategories therein, noting statistical significance where appropriate to demonstrate a reasonable conclusion that the findings relate to real-world differences between consumers' perceptions before co-creation of a hybrid meat product versus after. In the tables, the following notation has been used alongside +CC figures where appropriate to indicate the level of the statistically significant difference from the −CC figures: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$.

3.1. Evaluation

The category of evaluation is of particular note, not only in isolation but especially when cross-referenced with figures from the other categories and subcategories that follow. Since this category exemplifies the spirit of the words that consumers gave, it highlights whether they are viewing the product—and the specific features of the product identified by the subcategories—as positive or negative. Neutral words (those with no clear positive or negative association) were also identified, as well as words that were ambiguous in that they were likely to have a positive or negative association that was impossible to determine without further context; for example, the adjective *optimistic* may imply a positive outlook, or it may be a negative warning as to the potential for the product to be successful. The total number of words in each Evaluation category used by speakers in each language before and after co-creation are presented in Table 5.

For all three languages, the number of positive words increased and the number of negative words decreased significantly ($p < 0.001$) following the co-creation task; the number of neutral and ambiguous words also decreased slightly in each case, indicating that there was a direct shift from negative to positive words after co-creation.

Table 6 shows the top 15 words used by the three groups of consumers before and after co-creation, with neutral and negative words highlighted in light and dark grey respectively. It is clear from this that the amount of negative words has been reduced, but it is also interesting to note the way in which specific words change in evaluation, sometimes from a negative word to its direct positive opposite. In most cases, before co-creation, consumers perceived the hybrid meat products as expensive, but this perception was diminished after the task, with Spanish consumers even using the word *cheap*, suggesting that they are now more amenable to paying more for the products (the possible interpretation of this word as meaning "poorly-made" seems unlikely given its contrast with *expensive* before co-creation). This seems plausible in light of the increased attention to nutrition, as indicated by the more frequent use of words such as *nutritious*, *nourishing*, and *balanced*, which made it to the top words following the co-creation task; the implication here is that consumers perceive a hybrid meat product as better value for money once they are more informed about its nutritional value. It is also noteworthy that lexical items pointing to positive taste experiences (*tasty*, *delicious*, *appetising*) remain in the top words in both conditions, whereas those that are negative (*tasteless*, *insipid*, *bland*, *boring*) disappear from this list.

In isolation, this could be considered a mixed result for the hybrid meat product market: on the one hand, it implies that consumers see such products very positively once they are more familiar with them and know what is included in the product or have some choice of what "goes in." On the other hand, this result highlights that informing or educating consumers about hybrid meat products and their ingredients is a key factor in determining consumer attitudes, since their first impressions before the co-creation were considerably more negative.

Evaluation was cross-referenced with the demographic of gender to determine any link to consumers' attitudes. Men were found to respond with more negative words than women both before and after co-creation for all three languages, to a statistically significant degree of $p < 0.05$ or greater. Accordingly, female consumers gave more positive responses than male consumers before co-creation in all three languages ($p < 0.01$ or greater), and after co-creation for Spanish and Danish ($p < 0.001$); in English, the difference in the number of positive words between men and women was not found to be statistically significant.

Evaluation was also cross-referenced with further demographic information regarding the age range, education level, and purchasing responsibility of the respondents, but no significant differences were observed; for this reason and those of space, these demographics were not further considered in the analysis.

3.2. Sensory

Although this category looked at all senses relevant to the consumption of food, the only subcategory that achieved a number of responses of any note was taste (Table 7). For this category, once again there was a clear and significant ($p < 0.001$) increase in positive words (*delicious*, *tastes good*, *well-seasoned*) and decrease in negative words (*gross*, *bland*, *weird flavours*) for all three languages following the co-creation of a hybrid meat product. This is particularly interesting since the consumers have not of course had the opportunity to taste the products between the two times at which they provided their responses; this implies that consumers' perceptions of taste can be "imagined" or primed by features of the product and its ingredients that they are exposed to during the task.

TABLE 4 Categories and subcategories with examples.

Semantic category	Semantic subcategory	Examples[a]
Evaluation	Positive	*great-tasting, I like it, recommend*
	Negative	*greasy, not enough, repellent*
	Neutral	*basil, recipe, umami*
	Ambiguous	*challenging, no meat, surprising*
Sensory	Appearance	*colourful, unappealing*
	Consistency	*chewy, stodgy*
	Smell	*fragrant, rank*
	Taste	*bland, yum*
	Texture	*crispy, rubbery*
Production	Ingredients	*falafel, olives*
	Nutrition	*high in vitamins, low salt*
	Process	*homemade, wok food*
	Side effects	*diuretic, flatulence*
Emotion	Confusion	*bewildered, I don't know what to say*
	Expectation	*doubt, sceptical*
	Intention	*I wouldn't buy it, yes please*
	Interest	*don't care, intriguing*
	Mood	*heart-warming, shocking*
	Trust	*misleading, trick*
Diets	Allergies	*gluten, lactose-free*
	Disorders	*anorexia, diabetes*
	Religion	*halal, sin*
	Veganism	*herbivorous, vegan shit*
	Vegetarianism	*not as good as vegetarian, veggie burger*
	Weight loss	*fat-free, slimming*
Quality	Freshness	*fresh, perishable*
	Healthiness	*digestible, immune-building*
	Innovation	*inventive, novelty*
	Naturalness	*laboratory, pretend*
	Potential	*profitable, waste of time*
	Prestige	*niche, snobbery*
	Price	*cheaper, overpriced*
Ethics	Animal welfare	*animal rights, cruelty-free*
	Environment	*environmentally-friendly, polluting*
	General	*kinder, more ethical*
Other	Brands	*Heck, Jamie Oliver*
	Choice	*available, rarity*
	Convenience	*flexible, practical*
	Trendiness	*fashionable, politically-correct*

[a]Examples include some of the most frequent words as well as phrasal responses.

3.3. Production

The subcategory of nutrition (Table 8) was of particular note in this category, showing the same trend that positive attitudes to nutrition (*rich in vitamins*, *nutritious*, *without saturated fat*) increased significantly ($p < 0.001$) for all languages following co-creation. In this case, there were very few negative (*fatty*, *lack of vitamins*) or ambiguous (*fat content*, *without carbohydrates*) words given relating to nutrition in any language or condition, and the handful of neutral words (*nutrition*, *protein*) did not change in any significant way.

There was a significant ($p < 0.001$) decrease in the amount that consumers in all languages discussed the ingredients of a hybrid meat product following its co-creation. While the overwhelming majority of words were neutral in nature, since they were merely references to the specific ingredients that could be found in the product (*pepper*, *chickpeas*), it shows that there is a shifting of focus among consumers of the topics that are of importance to them once they have engaged in a co-creation task. Indeed, cross-referencing the subcategories of ingredients and nutrition demonstrated that, prior to co-creation, responses relating to ingredients were significantly ($p < 0.001$) more prevalent than those relating to nutrition, but that this statistical significance is reversed following co-creation—that is, responses relating to nutrition were significantly ($p < 0.001$) more prevalent than those relating to ingredients. This suggests that, by becoming more intimately involved with the process of creating a hybrid meat product, consumers are prompted to think more carefully about its nutrition rather than the top-level ingredients that it contains; this may have important implications for the impact of co-creation on consumers' understanding of nutrition and the healthiness of their diets.

3.4. Emotion

Consumer confusion (Table 9), as indicated by words that overtly expressed confusion (*bewildered*, *complicated*) or those that implied it through a lack of knowledge (*why*, *I don't know*), formed only a small number of responses both before and after co-creation; nevertheless, there was a statistically significant decrease in its prevalence for English ($p < 0.01$), Spanish ($p < 0.05$), and Danish ($p < 0.025$). The number of responses in the subcategory of interest also decreased, although it may be that some of these, such as *intriguing*, indicated a desire to know more about hybrid meat products which was somewhat sated by the end of the co-creation task.

Consumers' perceptions relating to intention were of particular note in this category: those that indicate positive intention (*appetising*, *I'd try*, *want to buy*)—that is, a desire to buy or eat the product—rose significantly ($p < 0.001$) across all three languages following co-creation, and, correspondingly, those that

TABLE 5 Frequency figures for subcategories of evaluation.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Positive	1,346	2,390****	1,376	2,448****	1,153	1,992****
Negative	1,038	308****	876	229****	993	368****
Neutral	594	366	751	410	725	537
Ambiguous	173	89	165	90	151	129
Totals	3,151	3,153	3,168	3,177	3,022	3,026

TABLE 6 Top 15 words given by consumers in each of the three languages both before (−CC) and after (+CC) co-creation, with neutral and negative words highlighted.

	English				Spanish				Danish			
	−CC		+CC		−CC		+CC		−CC		+CC	
	Word	Fq.	Word	Fq.	Word	Fq.	Word	Fq.	Word	Fq.	Word	Fq.
1	Healthy	237	Tasty	450	Healthy	361	Tasty	509	Healthy	177	Healthy	318
2	Tasty	141	Healthy	363	Tasty	102	Healthy	508	New	77	Delicious	145
3	Tasteless	116	Different	132	Vegan	91	Nutritious	165	Tasteless	70	Tasty	136
4	Expensive	98	Nutritious	104	Expensive	82	Appetising	74	Expensive	68	Exciting	101
5	Different	92	New	67	Insipid	80	Good	69	Boring	67	New	90
6	Vegan	82	Interesting	65	Weird	77	Natural	59	Taste	67	Tasteful	69
7	Bland	80	Healthier	59	Vegetarian	63	Different	57	Healthier	54	Taste	65
8	Healthier	54	Good	41	Flavour	59	Original	48	Exciting	51	Healthier	55
9	Fake	52	Unique	41	Natural	59	Balanced	44	Environmentally-friendly	49	Different	54
10	Vegetarian	51	Ethical	39	Different	51	Cheap	41	Different	48	Environmentally-friendly	51
11	Boring	43	Nice	39	Ecological	51	Delicious	36	Environment	45	Interesting	44
12	Interesting	43	Spicy	36	Artificial	44	Flavour	34	Delicious	43	Nourishing	44
13	Sustainable	43	Delicious	34	Vegetable	42	Weird	34	Vegetarian	39	Expensive	41
14	New	40	Nutritional	30	Fake	41	Expensive	33	Vegan	37	OK	40
15	Good	38	Fun	29	Sustainable	39	Novel	33	Interesting	33	Easy	34

TABLE 7 Frequency figures for subcategories of sensory.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Appearance	26	15	29	23	45	32
Consistency	31	43	29	34	38	30
Smell	5	2	3	5	9	9
Taste	528	729	328	628	331	533
Texture	54	17	36	17	31	22
Totals	644	806	425	707	454	626

TABLE 8 Frequency figures for subcategories of production.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Ingredients	213	117****	326	189****	318	239****
Nutrition	88	236	102	266	63	185
Process	18	8	20	10	22	16
Side effects	1	0	3	6	3	0
Totals	320	361	451	471	406	440

TABLE 9 Frequency figures for subcategories of production.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Confusion	55	26***	41	24*	50	28**
Expectation	8	3	14	12	26	17
Intention	70	98	99	158	81	96
Interest	111	94	40	26	143	82
Mood	22	66	51	34	75	136
Trust	39	21****	88	26****	69	28****
Totals	305	308	333	280	444	387

TABLE 10 Frequency figures for subcategories of diets.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Allergies	3	0	1	0	6	0
Disorders	0	0	1	1	1	0
Religious	1	0	0	0	2	0
Vegan	86	4****	101	9****	53	2****
Vegetarian	73	18****	72	11****	49	10****
Weight loss	11	5	36	20	2	6
Totals	174	27	211	41	113	18

TABLE 11 Frequency figures for subcategories of quality.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Freshness	23	22	10	8	8	16
Healthiness	341	466	466	609	292	431
Innovation	197	302****	220	227	207	195
Naturalness	205	75	309	114	197	70
Potential	80	76	69	57	79	69
Prestige	16	11	21	18	7	8
Price	144	78	122	115	110	92
Totals	1,006	1,030	1,217	1,148	900	881

TABLE 12 Frequency figures for subcategories of ethics.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Animal welfare	20	6	13	6	38	28
Environment	152	72	218	141	282	206
General	45	73	23	42	27	28
Totals	217	151	254	189	347	262

indicated negative intention (*avoid*, *no thanks*, *I'm not eating that*) fell significantly ($p < 0.01$), again across all languages. It is clear then that the co-creation task undertaken by consumers had a positive effect on their WTT and WTB that prompts further investigation.

A relatively small number of words relating negatively to trust (*deceptive*, *scam*, *swindle*) were found before co-creation, forming the majority of the words relating to this subcategory. Following the co-creation task, such words were found to have decreased in use significantly ($p < 0.001$) for all three languages, although there was little or no rise in the number of positive words relating to trust; rather, the topic seemed to no longer be of focus to consumers once they had undertaken the task and understood how hybrid meat products are made and the science behind them.

TABLE 13 Frequency figures for subcategories of other.

Semantic subcategory	English		Spanish		Danish	
	−CC	+CC	−CC	+CC	−CC	+CC
Brand	53	2	3	1	7	2
Choice	43	38	53	45	59	58
Convenience	30	82	17	45	21	70
Trendiness	93	39****	58	18****	57	23****
Totals	219	161	131	109	144	153

Only a small number of consumer responses were related to mood, and there was a general tendency toward those that were positive in meaning (*delightful*, *exciting*, *inspirational*). These positive mood words increased significantly ($p < 0.001$) for English and Danish consumers, but there was no change to be found for Spanish consumers.

3.5. Diets

Overall there were very few words for any of the diet-related subcategories (Table 10). In this category, consumers spoke most often about vegetarianism (*semi-vegetarian*, *veggie sausages*) and veganism (*vegan-mad veganish*), and there was a statistically significant ($p < 0.001$) decrease in words relating to these topics following co-creation for all three languages. Since the majority of words for vegetarianism and veganism were neutral in any case, it is likely that this topic simply became irrelevant for many consumers once they had learned more about hybrid meat products and the fact that they do contain meat (and are hence not vegetarian or vegan products). There is the wider implication here that the proper marketing of these products to highlight their meat content is likely to increase the number of consumers who are willing to try them as they will not be so easily dismissed by meat-eaters as suitable only for vegetarian or vegan diets.

3.6. Quality

One important focus for many consumers—and indeed for manufacturers—was the price of the hybrid meat products (Table 11). For English consumers, the number of responses related to this topic decreases following co-creation, but for Spanish and Danish consumers it remains a topic of interest. However, by cross-referencing with evaluation scores, it is clear that the number of negative responses relating to price (*expensive*, *overpriced*, *unaffordable*) decreased significantly for English and Spanish ($p < 0.001$) as well as Danish ($p < 0.025$) consumers. An increase in positive words relating to price (*cheaper*, *economical*, *worth the price*) was significant only for Spanish consumers ($p < 0.001$).

The healthiness of the products was a topic of a great amount of focus for consumers, and for all three languages over 94% of words relating to healthiness were positive in nature (*good for you*, *wellbeing*, *it's healthier*) even before the co-creation task. Despite this, positive responses concerning healthiness increased significantly ($p < 0.001$) to over 98% for all languages following the task. This is in contrast to some extent to the concept of naturalness, which was more often perceived negatively by many consumers both before and after the co-creation task. Nevertheless, the degree to which consumers responded with negative words about naturalness (*artificial*, *fake*, *Frankenstein*) decreased significantly ($p < 0.001$) for all languages following co-creation and the increased understanding of how hybrid meat products are developed.

The perception of innovation of the hybrid meat products was addressed by a number of consumers and was done so with an overwhelmingly positive outlook (*progressive*, *pioneering*, *futuristic*); this remained constant for Spanish and Danish following the co-creation task, while for English it increased further to a statistically significant extent ($p < 0.001$).

3.7. Ethics

For words relating to ethical considerations (Table 12)—mostly restricted to matters of the environment and animal welfare—consumers generally gave positive responses (*more climate-friendly*, *animal-friendly*, *no guilt*). Following co-creation, these generally seemed to decline, although the shift was not majorly significant and did not result in any increase in the number of negative words relating to ethical matters. In general, then, ethical topics were of less interest to consumers following co-creation, likely because of the increase in focus of matters relating specifically to the product that they had created—its naturalness, healthiness, affordability, etc.—and because, once an ethical issue had been registered upon the first viewing of the product, it did not seem necessary to repeat this fact after co-creation.

3.8. Other

The subcategory of convenience (Table 13) shows that many consumers were concerned with how easy the products would be to prepare and cook, but in general this was the case only following co-creation. While topics such as ingredients, animal and environmental welfare, and vegetarianism/veganism were more frequent before the task, once they had created their own hybrid meat product many consumers focused more frequently on the level of convenience of the products, doing so in a positive way (*easy to cook*, *straightforward*, *helpful*), and increasingly so to a significant degree ($p < 0.05$) in all languages.

Some consumers also commented on the trendiness of the product; this subcategory produced a number of words that were ambiguous in nature, since the perception that something is "trendy" or "fashionable" is not always considered a positive attribute. Following the co-creation task, the number of words relating to trendiness fell significantly ($p < 0.001$) in all languages, and this was primarily from those that were evaluated as negative (*gimmicky*, *faddish*, *bandwagon*) or ambiguous (*modern*, *fashionable*, *politically-correct*). In the same way as figures for the subcategories of vegetarianism and veganism, it seems that perceptions of the products as being limited to a specific group or type of person are decreased once the co-creation task has been completed.

4. Conclusion

It is clear that the process of co-creation results in much more favourable perceptions of hybrid meat products. Following co-creation, consumers have been shown to have a more positive perception of the nutritional value of a product, as well as more trust and stronger intentions to try or buy them. Regarding taste—a factor of great importance to consumers—the majority of negative considerations of taste disappear following co-creation; while this could imply that consumers might decide they would like the product after all, it might also suggest that those consumers who would not personally find the product appealing can at least appreciate the positive aspects of the product as an available option in the supermarket. In addition, while the majority of consumers consider the products healthy even before co-creation, following the task these perceptions are significantly increased and any concerns about the unnaturalness of the hybrid meat products are diminished.

While it is possible that there is an effect here caused by the fact that the consumer has had a hand in the products development (a kind of "I made it" effect), the key difference following co-creation is that the consumer now has a better understanding of what the product is and how it is developed. This is exemplified by the words that the consumers used to describe them, particularly through (1) a decrease in words relating to confusion, (2) a greater focus on nutritional value over basic ingredients, and (3) a decrease in words such as *vegetarian* and *vegan* that highlight misunderstandings of the nature of a hybrid meat product. It is reasonable to conclude therefore that a major barrier to the positive perception of hybrid meat products is a lack of understanding about their nature and the processes involved in their development. This finding can be seen in a positive light: to rephrase a paragraph from section 3.1, although there is a considerable proportion of consumers who perceive hybrid meat products negatively, there is hope in that these perceptions can be significantly minimalized through education. However, the package may not be the place to undertake this education, since consumer opinions can be formed very quickly and on very little information (18); instead, it is likely that consumers will need to have a positive perception of a hybrid meat product before they enter the supermarket. Future work should focus on understanding the best way to communicate to consumers what hybrid meat products are and what their potential benefits might be. Another challenge lies in the fact that hybrid meat products currently are somewhere "in-between," so while they surely do not belong to the vegan and vegetarian isles in the supermarkets, they should be given a dedicated and somehow highlighted section in the meat aisle to point out their differences from the meat-only products available.

Perhaps owing to the fact that hybrid meat products are an innovation to most markets, few differences were found between the three languages studied. Nevertheless, those differences that were found may be of importance: Danish consumers focused significantly more on ethical issues and gave more responses in relation to emotion, while they and Spanish consumers were both more concerned with the production process (including both the ingredients and the nutritional value) compared to English consumers. These differences in focus suggest that different marketing strategies should be employed in each market in order to successfully appeal to the consumers therein.

The results of this study show that co-creation matters for consumers' perceptions of certain aspects of hybrid meat products, and therefore any new launches should be carefully co-created with consumers from the outset. The food industry should use co-creation tools more as they can provide valuable insights before products are developed and launched into the market, and therefore increase the chances of successful, competitive and tailored products on the shelves. In any case, the need for greater education regarding the nature of hybrid meat products is clear, and should be the first priority.

4.1. Limitations and further study

As a pioneering examination of the topic of attitudes to hybrid meat products in this way, this study has generally taken an approach that is broader than it is deep. It covers a large number of categories of words given by participants to analyse the overall trends in relation to positivity and negativity, and how these are influenced by an online co-creation task that helps educate consumers about the nature of hybrid meat products. A key area for future study, therefore, is to examine these trends in greater detail, with reference to demographic qualities of the respondents and any differences to be found therein. Although categories such as gender, age, education level and purchasing responsibility were considered initially, no significant differences were identified on the surface level and so these were not pursued further. It is highly anticipated that this type of study could be repeated with greater emphasis on demographic characteristics of the consumers now that the most significant concerns have been identified and that the positive benefits of the co-creation task on consumer attitudes has been established. Given that food choices often have to do with lifestyle preferences, further research would benefit from operationalising and including lifestyle as a factor alongside established demographic variables such as age and gender.

The socioeconomic situations in the United Kingdom, Spain, and Denmark have been addressed in this study, but, needless to say, the door has been opened for the same types of examination of further situations. These could be expanded within the same countries, such as a comparison of attitudes within each of the Home Nations of the United Kingdom, or could be widened to consider the same languages as spoken in alternative socioeconomic areas, such as the United States and Canada, Mexico and South America, and Greenland. Finally, there is great scope to broaden the study into further languages, in particular those spoken in Europe within the same socioeconomic bloc, such as French, German, and Swedish.

The approach taken here has combined qualitative with quantitative techniques, employing corpus-linguistic methods to analyse attitudes based on frequency counts that rise and fall following the co-creation task. Further studies could benefit from this approach, but it would also be invaluable to employ more qualitative research methodologies such as focus groups with consumers in each country and language, as these may yield more comprehensive and nuanced results. Beyond lexical prompts, such focus groups could involve sensory stimuli to tap into more immediate corporeal perceptions of hybrid meat products. Although the technique of spontaneous free word associations has been identified as a powerful tool to understand consumers' perceptions, expectations and their food behaviour, future studies could complement word associations with other projective techniques, such as those involving, for example, story techniques and completion tasks to gain more holistic insights into consumers perceptions of hybrid meat products [e.g., (14)].

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by University of Reading Ethics Committees. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SG collected the data for the study and contributed to refining the final version. CR organised the database and completed the statistical analysis. SJ and CR performed data categorisation and analysis and wrote the first draft. All authors contributed to the article and approved the submitted version.

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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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Consumer perception of "artificial meat" in the educated young and urban population of Africa

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African's population is expected to grow especially in cities to reach about 2.5 billion in 2050. This will create an unprecedented boom in the demand for animal products over the coming years which will need to be managed properly. Industry stakeholders worldwide have been touting the potential benefits of "artificial meat" in recent years as a more sustainable way of producing animal protein. "Artificial meat" is therefore moving into the global spotlight and this study aimed to investigate how African meat consumers of the coming generations perceive it, i.e., the urban, more educated and younger consumers. Three surveys were conducted with more than 12,000 respondents in total. The respondents came from 12 different countries (Cameroon, Congo, -DRC Democratic Republic of Congo, Ghana, Ivory Coast, Kenya, Morocco, Nigeria, Senegal South Africa, Tanzania and Tunisia). Respondents in this survey prefered the term "artificial meat". This term was therefore used throughout the survey. "Artificial meat" proved to be fairly well known in the surveyed countries as about 64% the respondents had already heard of "artificial meat." Only 8.9% were definitely willing to try "artificial meat" (score of 5 on a scale of 1–5) mostly males between 31 and 50 years of age. Furthermore, 31.2% strongly agreed that "artificial meat" will have a negative impact on the rural life (score of 5 on a scale of 1–5) and 32.9% were not prepared to accept "artificial meat" as a viable alternative in the future but were still prepared to eat meat alternatives. Of all the results, we observed significant differences in responses between respondents' countries of origin, age and education level with interactions between these factors for willingness to try. For instance, the richest and most educated countries that were surveyed tended to be more willing to try "artificial meat." A similar pattern was observed for willingness to pay, except that gender had no significant effect and age had only a small effect. One major observation is that a large majority of respondents are not willing to pay more for "artificial meat" than for meat from livestock.

KEYWORDS

consumer survey, cultured meat, cell-based food, food security, willingness to engage, livestock

Introduction

The African population is expected to reach about 2.5 billion people in 2050. About 80% of this increase will occur in cities, with nearly 1.5 billion Africans living in urban areas (1). This increase in urban population along with increased income is set to increase the demand for animal-sourced food (2–4).

The livestock sector in some African countries is the fastest growing agricultural subsector (5). It contributes not only to food and nutrition security but also to economic growth by providing important foreign exchange through increased trade within and between African countries, as well as with other regions, such as the Middle East (6). Africa's livestock accounts for one third of the world's livestock population (3) and about 40% of agricultural GDP in Africa, ranging from 10 to 80% depending on the country (6).

Unfortunately, African livestock farming systems are less efficient and productive than their counterparts in more developed countries with smallholders being the main suppliers of animal-derived food (6). These smallholders are also far from markets and depend on abattoirs with limited infrastructures, thereby making it difficult to meet the growing demand for meat (7).

Between 2018 and 2020, one African person consumed on average 13 kg of meat per year, with chicken being the most consumed at 5.75 kg *per capita*. By 2030, Africa's meat consumption is expected to increase by 30% and growth in consumption will outpace the expansion of domestic production (7), and the amount of meat consumed is expected to increase to 26 kg of meat in 2050 (6, 8). Consumption patterns across Africa vary significantly; some countries consume as little as 10 kg of meat per person, around half of the continental average. Countries with higher incomes such as South Africa, consume between 60–70 kg of meat per person (9).

In addition to this demographic pressure, livestock farming systems across Africa will have to cope with climate change and develop sustainable methods of production. African livestock production already has a significant impact on the environment (10). More than 70% of agricultural greenhouse gas emissions in Africa comes from the livestock sector, dominated by enteric methane (CH_4) emissions (3).

Furthermore, the most significant environmental impacts and nutritional issues associated with animal-sourced food consumption are predicted to occur in Africa and as well as in other low- and middle-income countries of the World (11). It will therefore be a challenge for Africa to produce meat quantitatively and qualitatively for its population. Consequently, there is a huge opportunity for the private sector due to the continent's swelling dietary needs. There will be a need for the private sector to invest in veterinary services, drugs, vaccines, animal feed and infrastructures. Smallholders, with limited production resources, cannot reach these objectives.

Given this context, and especially with regard to the expected environmental challenge and the growing demand for animal protein in Africa, "artificial meat" appears to be a viable solution as suggested by its proponents. This novel food product makes use of ground-breaking technologies such as tissue culture and bioreactor engineering to increase the production of meat alternatives that may become a threat to the conventional meat industry (12, 13). "Artificial meat" is produced by *in vitro* tissue or cell culture, or by three dimensional (3D) printing of meat (14). "Artificial meat" currently faces its own problems, such as technological barriers, sensory, nutritional, health and safety challenges, in order to be fully accessible to developing food meat markets (15, 16).

"Artificial meat" is a technical revolution, but it could also be considered as a potential economic and societal revolution, which could disrupt the traditional meat sector (17). Consumer acceptance of this novel product has been studied in many European (18–22), American (23, 24) and Asian countries (25), but little is known about the potential acceptance of "artificial meat" in African countries, despite the world's greatest challenges in terms of meat demand, climate issues and socio-economic challenges as described above.

The aim of this study is therefore to explore the responses of African consumers of the next generations (i.e., mainly urban, more educated and younger consumers) to relevant questions in order to investigate their attitudes, outlook, potential acceptance, and willingness to engage with "artificial meat," and to provide insight into the factors that may lead to the acceptance of "artificial meat" in the general context of Africa.

Materials and methods

Design of the questionnaire

Three surveys were conducted. All surveys adhered entirely to the ESOMAR (European Society for Opinion and Market Research) guideline for ethical online research (ESOMAR, 2011). Indeed, all respondents had to give their explicit informed consent to take part in the survey and their personal data was protected. In addition, respondents' data was collected in an anonymous way with a "do not wish to answer" option and with no personally identifiable information. This research was conducted in accordance with the published guidelines of the countries in which it was performed with, when required, the approval of ethics committees (such as in Brazil: CAAE number: 37924620.5.0000.5404 (23)).

As an introduction to all the surveys, basic information on "artificial meat" was provided with a small text and an illustration to avoid confusion with any other type of "artificial meat," e.g., from plant proteins (Figure 1). In at least one question, different wordings (such as "cell-based meat," "cultured meat," "lab meat," etc) were used for better understanding and to avoid any bias in the answers. In this specific question, respondents were asked for the best wording of this new product.

The three surveys were organized around six sets of questions:

1. **Socio-demographic information:** this involved the collection of information such as gender, age, education level, area of work, net monthly income, meat consumption, and familiarity with "artificial meat" (Supplementary material - Questions 1 to 8).
2. **General questions:** These questions were asked as a preamble regarding the respondents' food purchasing criteria and whether they had ever heard of this product (Supplementary material - Questions 9–10).
3. **Attitude towards societal challenges:** the objective here was to collect information on the respondents' attitude towards the societal challenges facing conventionally produced meat (meat from conventionally raised farm animals) and "cell-based meat," with regard to ethical, environmental, traditional meat industry, and rural life issues (Supplementary material - Questions 11 to 16).
4. **Characteristics of the product.** Questions were related to the perception of healthiness and eating quality of "artificial meat" (Supplementary material—Questions 17–18).

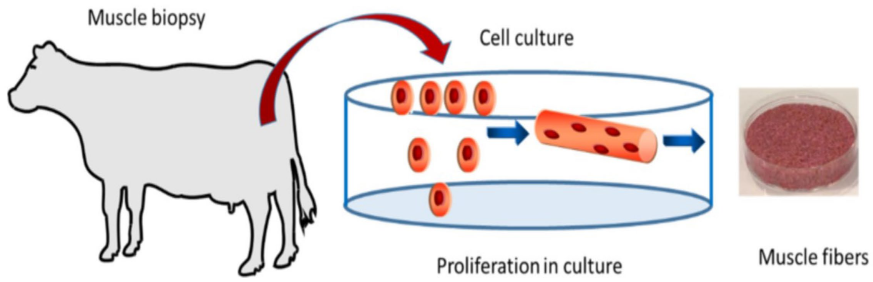

FIGURE 1
Introduction of "artificial meat" provided to respondents adapted from (23).

5. **Potential interests:** these questions aimed to evaluate consumer acceptance of "artificial meat." They also had the aim to capture personal perceptions of this novel food compared to conventionally produced meat, including a question on how to name this product (Supplementary material—Questions 19 to 27).
6. **Development strategies:** the respondents were asked about future development strategies for the marketing of "cell-based meat" (Supplementary material—Questions 28 to 32).

Whereas the third survey included the six groups of questions, the survey 1 included the 4 first groups, and survey 2 the 2 last.

Data collection

Respondents were randomly recruited using the KASI Insight platform. KASI Insight is an African-based consulting firm that conducts surveys for market research. Kasi insight implemented a computer assisted self-interviewing (CASI) process as its main methodology which is conducted at respective connected locations (businesses, community centers, etc.) which offer respondents access to complete the survey on a desktop, without incurring data costs. CASI is a technique for survey data collection in which the respondent uses a computer to complete on-line the survey questionnaire without an interviewer administering it to the respondent. This assumes the respondent can read well (enough) and understand either English or French.

A primary rationale for CASI is that some questions are so sensitive that if researchers hope to obtain an accurate answer, respondents must use a highly confidential method of responding.

The CASI process includes multiple quality controls, including trained interviewers available at the interview sites to assist respondents when they have questions. The CASI process also include: (1) Cross-checking and authentication: All completed surveys are checked and 20% of questionnaires are cross-checked. (2) Verification of data entry: validation and verification include predefined survey rules and matching processes.

Data were collected through monthly surveys. The target population for these surveys was the adult population of major urban cities in each of the participating countries. In most of these countries, this population is representative of the economically active population, and the main decision makers in household purchases. Rural residents were therefore excluded from the surveys.

Survey responses were voluntary. Each interview took an average of 15 to 20 min. Interviews were conducted in English and French. No quotas were imposed on the survey, allowing city residents of all demographics a fair chance to be included in the survey.

The first and second surveys were conducted in the main urban centers of 12 African countries: Cameroon (Yaoundé and Douala), Congo (Brazzaville), DRC Congo (Kinshasa), Ghana (Accra, Labadi, Teshie, Nunua, Kumasi), Ivory Coast (Abidjan, Yopougon, Angre, Abodo, Bouake, Williamsville), Kenya (Nairobi, Mombasa, Nakuru), Morocco (Rabat, Casablanca), Nigeria (Lagos, Abuja, Port harcourt, Abia), Senegal (Dakar), South Africa (Johannesburg, Cape Town), Tanzania (Dar Salaam, Arusha) and Tunisia (Tunis).

The complete survey process flow is shown in Figure 2. The first survey was constituted of 21 questions. This survey (Supplementary material-Questions 1 to 19, then 29 and 31) analyzed environmental and ethical concerns of the respondents (global warming, animal welfare, animal suffering, and slaughter) as well as the disadvantages associated with conventional meat as perceived by these respondents (limited agricultural resources and population growth).

The second survey (Supplementary material-Questions 1 to 7 and 20 to 32, excluding 29) analyzed respondents' acceptance of "artificial meat" through their willingness to try (WTT), willingness to pay (WTP), and willingness to eat regularly (WTE).

The third survey was a combination on the first 2 surveys which was constituted of 33 questions. This survey analyzed both aspects (societal challenges and respondent acceptance) with fewer respondents (n = 1,111) from only 5 countries (Cameroon, Ghana, Kenya, Morocco, and South Africa) to represent different parts of Africa (Central, West, East, North, and South, respectively) and with the greatest potential to obtain more responses in a limited time period due to time constraints. The results of the two surveys were compared to assess the replicability of the methodology.

An average sample of 500 people per country was surveyed, targeting men and women over the age of 18. Because the population size of these sampled cities is generally greater than 500,000, the minimum recommended sample size for this population is 377, and we collected between 728 and 1,345 answers per country (for Cameroon, Ghana, Kenya, Morocco and South Africa) after pooling data from the first or second survey on one hand and from the third survey on the other hand in order to explore respondents' opinions.

Pooling two or more cross-sectional survey data sets (i.e., stacking comparable data sets on top of one another) can serve different

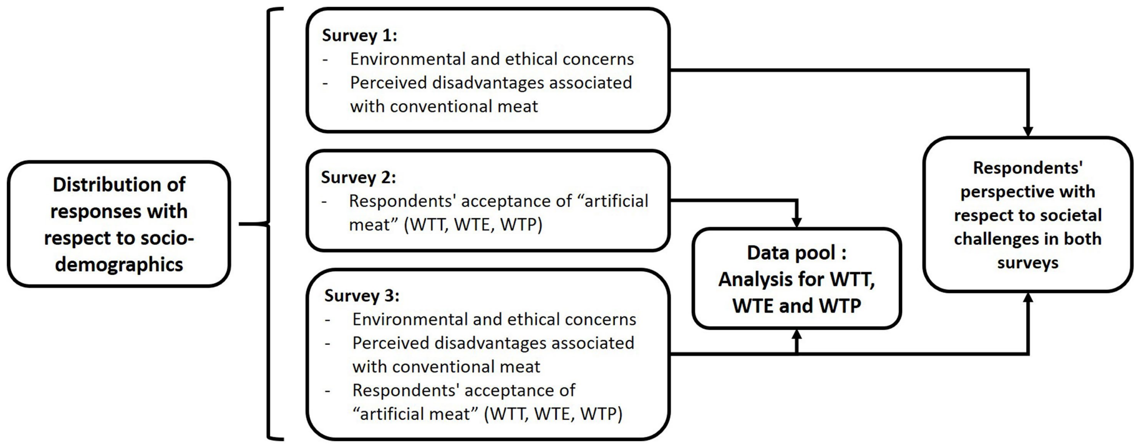

FIGURE 2
Survey process flow.

purposes including to increase the sample size in hopes of improving the precision of a point estimate. The latter purpose is especially common when making inferences on a subgroup, or domain, of the target population insufficiently represented by a single survey data set (26). Consequently, answers to questions numbers 25 to 28 related to WTT, WTE and WTP for 5 countries (Cameroun, Ghana, Kenya, Morocco and South Africa) were pooled to be analyzed together. For all other questions, results were compared between surveys without pooling to take into account data from the 12 countries from surveys 1 ad 2.

Statistical analyses

The data were analyzed using R software (Version 4.0.2) (27). For most of the questions, respondents were asked to provide responses on a Likert-scale: strongly disagree (score 1), somewhat disagree (score 2), undecided (score 3), somewhat agree (score 4), and strongly agree (score 5), with the exception of a few qualitative variables which were then coded as quantitative variables to assess the influence of socio-demographic variables on WTT, WTP and WTE. The chi-2 test was used to compare the distribution of results between the two surveys.

WTT was coded quantitatively from "Definitely not" = 1 to "Definitely yes" = 5 and WTP: from "Much less" = 1 to "Much more" = 5. For WTE, the question was initially asked with multiple responses and was coded as "1" (for respondents who answered: In restaurants, At home, In prepackaged ready-to-eat meals, I do not want to eat "artificial meat" regularly, Other) and "2" (do not want to eat "artificial meat" regularly).

The initial investigations targeted the relationships between socio-demographic information and variables of willingness by means of ANOVA supplemented with a pairwise comparison between significant groups using Tukey HSD (by the R package "agricolae"). The one-way analysis of variance (ANOVA) was used to highlight any statistically significant differences between the means of the different groups corresponding to the levels of each factor of variation studied. The model was performed with the data collected from the second and third survey and for 5 different countries (Cameroon, Ghana, Kenya, Morocco and South Africa) with the different socio-demographic factors: y = Country + Gender + Age + Education + Income + Country × Gender + Country × Age + Country × Education + Country × Income + Gender × Age + Gender × Education + Gender + Income + Age × Education + Age × Income + Income × Age. ANOVA was run a second time with only the significant factors and significant interactions included in the model. Differences were considered significant at a value of $p < 0.05$. Lsmeans (Least-Squares Means which are means that are computed based on a linear model such as ANOVA) were calculated in order to detect statistical differences across the different groups (28).

After performing the ANOVA, the effect size was investigated. Effect sizes could be used beyond significance tests (*p*-values), because they estimate the magnitude of effects, independent from sample size (29). The effect size was evaluated in R software (Version 4.0.2) with the package "sjstats." The effect size was calculated by eta squared -denoted as η^2. The eta squared corresponds to the total variability in the dependent variable accounted for by the variation in the independent variable. It is calculated as the ratio of the sum of squares for each group level to the total sum of squares. It can be interpreted as percentage of variance accounted for by a variable (30). The effect sizes are reported in the Supplementary material. Effect sizes varied between 0.01 and 0.02. for the different variables, which is considered to be low to moderate (30) (< 0.01 corresponds to a Small effect size, between 0.01 and 0.06 to a medium effect size and > 0.14 correspond to a large effect size).

In addition, a Principal Component Analysis (PCA) (by the R packages "FactoMineR" and "Factoextra") was performed with the quantitative data of the third survey for which all responses from the same respondents were available to represent and model multidimensional point cloud surveys, showing whether relationships exist between the variables as previously done with similar data (19). PCA allows for the calculation of new variables, called principal components, which capture the variability in the data. This enables information to be described with fewer variables than originally present. The principal components are linear combinations of the original variables. The first principal component is the combination of variables that explains the greatest amount of variability in the data. The second and subsequent principal components describe the maximum amount of remaining variability and must be independent (orthogonal) between them and to the first principal component.

Results

The sociodemographic characteristics of the respondents of the three surveys are detailed in Table 1. The result description follows the outline below:

- Comparison of socio demographics data between the 3 surveys (questions 1 to 8).
- Comparison of results between survey 1 (in 12 countries) and survey 3 (in 5 countries) concerning respondents' perspective in relation to societal challenges (questions 11 to 16 in common between surveys 1 and 3).
- Comparison of results between survey 1 (in 12 countries) and survey 3 (in 5 countries) concerning the respondents' potential interest in "artificial meat" (questions 19 to 27).
- Comparison of results between survey 2 (in 12 countries) and survey 3 (in 5 countries) (questions 19 to 31 in common between both surveys) concerning the potential acceptance of "artificial meat" by the respondents. Then, analysis of pooled results of WTT, WTE and WTP from 5 counties in common between surveys 2 and 3 (questions 25 to 28).
- Potential drivers of acceptance of "artificial meat" from data of survey 3 (answers to all questions from respondents of 5 countries).

A summary of the respondents' profile and answers is shown in Figure 3.

Socio-demographic data for all respondents

The first survey had 5,485 respondents, the second survey had 5,528 (the percentages of respondents per country in both surveys varied between 7 and 10%) and the 3rd survey had 1,111 responses (the percentages of respondents per country varied between 19 and 20%). The socio-demographic characteristics of the respondents for all surveys are shown in Table 1.

All surveys had the same structure for gender and age with a majority being males representing 50.3, 52.9 and 58.2% of respondents in surveys 1, 2 and 3, respectively, and respondents between 31 and 50 years of age being the largest group (68.3%, 65%, and 49% respectively).

Most of the respondents were graduates in all surveys (58.7%, 56.6%, and 61.5% respectively) and had a monthly income of less than 1,500 USD (58.5%, 57.5%, and 43.6% respectively) (Table 1).

The respondents ate meat regularly, several times a week in in surveys 1 and 3 (38% in survey 1 and 38.2% in survey 3) and had heard of "artificial meat" (63.9% in survey 1 and 55.3% in survey 3) (data not shown).

In both surveys, most of the respondents were not scientists, and the majority did not work in the meat sector (54.9% in survey 1 and 50.5% in survey 3) (data not shown).

Respondents' perspective in relation to societal challenges

For all questions related to societal challenges (Table 2), no statistical difference was observed between the results of the two surveys which addressed these issues.

In surveys 1 and 3, most of the respondents disagreed with the idea that livestock can cause environmental problems (43.3% of responses

TABLE 1 Distribution of responses with respect to socio-demographics.

Question	Response option	Survey 1		Survey 2		Survey 3	
		Number of responses	Percentage (%)[a]	Number of responses	Percentage (%)[a]	Number of responses	Percentage (%)[a]
Gender	Female	2,725	49.7	2,602	47.1	464	64,741.8
	Male	2,760	50.3	2,926	52.9	647	58.2
Age	18–30 years	1,583	28.9	1763	31.9	517	46.5
	31–50 years	3,745	68.3	3,593	65.0	544	49.0
	>51 years	157	2.8	172	3.1	50	4.5
Education	Primary school	216	4.0	205	3.7	27	2.4
	High school	412	7.5	410	7.4	52	4.7
	Undergraduate	149	2.7	168	3.1	25	2.25
	Technical Training	1,490	27.1	1,615	29.2	324	29.2
	Graduate	3,218	58.7	3,130	56.6	683	61.5
Monthly income	Under USD1,500	3,208	58.5	3,179	57.5	484	43.6
	More than USD1,500	2,277	41.5	2,349	42.5	627	56.4
Total		5,485	100	5,528	100	1,111	100

[a]Percentage of people who answered the questionnaire.

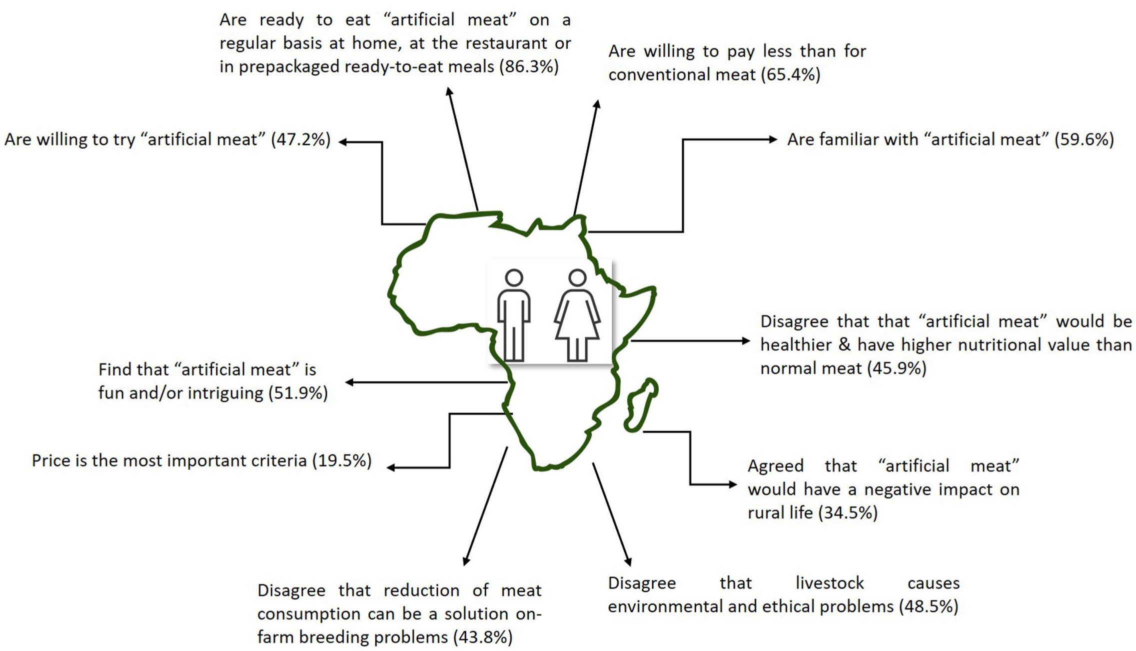

FIGURE 3
Respondents' profile summary towards "artificial meat".

were 1 and 2 on a scale of 0–5 point in survey 1 and 50% in survey 3) and ethical problems (48.8% in survey 1 and 52.1% in survey 3).

The respondents in both surveys also disagreed with the reduction of meat consumption as a solution to the problems caused by on-farm breeding (39.3% of responses were 1 or 2 in survey 1 and 48.3% in survey 3). The respondents disagreed on the fact that "artificial meat" would be healthier (36.7% of responses were 1 or 2 on scale of 0–5 in survey 1 and 55.1% in survey 3) and tastier (40.1% of responses were 1 or 2 on a scale of 0–5 in survey 1 or 52.3% in survey 3) than conventional meat. The respondents in both surveys agreed that "artificial meat" would have a negative impact on rural life (42.1% of responses were 4 or 5 in survey 1 and 27% in survey 3).

Some respondents expressed some emotional resistance to "artificial meat" in both surveys (22.9% of responses were 4 or 5 in survey 1 and 14.2% in survey 3) (Table 2).

Potential interest in "artificial meat"

In both surveys, respondents considered price (18.8% in survey 1 and 20.1% in survey 3) as the most important criterion when purchasing meat, followed by meat quality (17.2% in survey 1 and 15.8% in survey 3) (Table 3). Some respondents in both surveys considered "artificial meat" as safe (14.2% in survey 1 and 18.1% in survey 3).

When asked how they perceive "artificial meat," respondents from both surveys followed the same pattern. Of the three options proposed, most consumers found it "fun and/or intriguing" in both surveys with 59.1% in the first survey and 44.7% in the third one. In the first survey, 22.7% found it "promising and/or acceptable" while 18.3% found it "absurd and/or disgusting." In the third survey, the figures were 39.3% and 15.9%, respectively.

The largest proportion of respondents in survey 1 are consumers of both meat and meat alternatives and did not consider artificial meat as a viable meat alternative (they represent 32.9% in Survey 1 and 25.8% in Survey 3), while the largest proportion in survey 2 did not eat meat substitutes and considered "artificial meat" as a viable alternative (they represent 33.4% in survey 3 and 28.8% in survey 1, Table 3).

In both surveys, ethical concerns were the most likely to convince respondents to eat "artificial meat" (13.8% in survey 1 and 17.3% in survey 3), while safety concerns were a major reason why respondents were not willing to eat "artificial meat" (13.9% in survey 1 and 12.3% in Survey 3). In addition, a significant proportion of respondents found "artificial meat" to be unnatural (20% in survey 3 and 12.7% in survey 1, Table 3).

In both surveys, most respondents preferred to consume "artificial meat" at home (25.9% in survey 1 and 30.0% in survey 2), followed by restaurants (23.9% in survey 1 and 29.3% in survey 2) and pre-packaged ready-to-eat meat (19.9% in survey 1 and 23.6% in survey 3, Table 3).

Majority of the respondents preferred the name "artificial meat" (18%) (followed by "Clean Meat": 13.66%; "Lab meat": 13.36%; "Cultured Meat": 13.22%; "Cellular Meat": 11.13%; "*In-vitro* Meat": 11.59%) and 61% agreed the product could be labelled as meat when commercialized, whereas 39% thought the opposite (data not shown).

Potential acceptance of "artificial meat"

Willingness to try (WTT)

In surveys 2 and 3, many respondents were willing to try "artificial meat." Indeed, in survey 2, 39.2% were willing to try

TABLE 2 Respondents' perspective with respect to societal challenges in both survey 1 and survey 2.

Question		Response (1: completely disagree—5: completely agree)				
		1	2	3	4	5
In your opinion does on-farm breeding cause important environmental issues, e.g., huge water consumption and greenhouse gas emissions?	Survey 1	794 (14.5%)	1,579 (28.8%)	1727 (31.5%)	1,138 (20.7%)	246 (4.5%)
	Survey 2	221 (19.9%)	334 (30.1%)	370 (33.3%)	159 (14.3%)	27 (2.4%)
Do you believe that on-farm breeding can cause important ethical problems (e.g., animal suffering, animal slaughter)?	Survey 1	859 (15.7%)	1813 (33.1%)	1,527 (27.8%)	1,056 (19.3%)	229 (4.2%)
	Survey 2	301 (27.1%)	267 (25%)	376 (33.8%)	147 (13.2%)	20 (1.8%)
In your opinion, can the potential problems of on-farm breeding be dealt with by reducing our meat consumption?	Survey 1	735 (13.4%)	1,420 (25.9%)	1717 (31.3%)	1,314 (24%)	298 (5.4%)
	Survey 2	243 (21.9%)	293 (26.4%)	374 (33.7%)	179 (16.1%)	22 (2%)
Do you believe that if people ate Artificial meat instead of conventional meat, it would improve the welfare of animals and reduce animal suffering?	Survey 1	656 (12%)	1,246 (22.7%)	1790 (32.6%)	1,437 (26.2%)	355 (6.5%)
	Survey 2	252 (22.7%)	276 (24.8%)	383 (34.5%)	180 (16.2%)	20 (1.8%)
Using the following rating scale, do you think that Artificial meat could negatively impact livestock farming and the meat industry (e.g., by reducing the number of jobs available?)	Survey 1	547 (10%)	1,055 (19.2%)	1,599 (29.1%)	1,764 (32.2%)	519 (9.5%)
	Survey 2	239 (21.5%)	270 (24.3%)	343 (30.9%)	205 (18.4%)	54 (4.9%)
Do you think that Artificial meat would have a negative impact on rural life?	Survey 1	503 (9.2%)	1,098 (20%)	1,570 (28.6%)	1713 (31.2%)	600 (10.9%)
	Survey 2	201 (18.1%)	278 (25%)	332 (29.9%)	231 (20.8%)	69 (6.2%)
To what extent do you believe that Artificial meat would be healthier & have higher nutritional value than normal meat?	Survey 1	724 (13.2%)	1,291 (23.5%)	1913 (34.9%)	1,185 (21.6%)	371 (6.8%)
	Survey 2	292 (26.3%)	264 (23.8%)	397 (35.7%)	132 (11.8%)	26 (2.3%)
In your opinion do you believe that Artificial meat is tastier compared to normal meat.	Survey 1	1,032 (18.8%)	1,171 (21.3%)	1,898 (34.6%)	1,095 (20%)	288 (5.2%)
	Survey 2	284 (25.6%)	297 (26.7%)	399 (35.9%)	118 (10.6%)	13 (1.2%)
In your opinion would you say that you have emotional resistance to trying out Artificial meat (e.g., disgust or nervousness)?	Survey 1	548 (9.9%)	1,516 (27.4%)	2,197 (39.7%)	853 (15.4%)	414 (7.5%)
	Survey 2	294 (26.5%)	288 (25.9%)	371 (33.4%)	112 (10.1%)	46 (4.1%)

"artificial meat" (8.9% definitely try and 30.3% probably try), 36.6% were unsure or not yet decided whether they would try "artificial meat" and 24.2% were not willing to try "artificial meat" (14.7% will probably not try, 9.5% will definitely not try). In survey 3, a majority (55.2%) is willing to try "artificial meat" (26.1% will definitely not, 29.1% will probably try) as in the first survey compared to 18.36% who are unwilling to try (4.7% definitely not, 13.7% probably not), with 26.5% of respondents being undecided (Table 3).

In survey 3, WTT was also significantly affected by the perceived impacts of conventional meat on livestock, rural life, the environment, ethics ($p < 0.0001$) and the interaction between the country and the frequency of meat consumption ($p < 0.0001$).

The pooled data for the 5 countries in common between surveys 2 and 3 was analyzed for 5 countries (Cameroun, Ghana, Kenya, Morocco and South Africa). The results showed that WTT differed significantly according to country, age, income and education (Figure 4; Table 1,). Interactions were significant between country

TABLE 3 Potential interest in "artificial meat" in both survey 2 and survey 3.

Question	Response options	Survey 1 and 2 (*n*=11,013)		Survey 3 (*n*=1,111)	
		Number of responses	Percentages (%)	Number of responses	Percentages (%)
Which of the following would you say are important considerations for you when you go to shop for meat? Which of the following would you say are important considerations for you when you go to shop for meat? (multiple choice question)	Ethics of how the meat was produced, e.g., were the animals allowed to roam freely	923	5.5	491	12.5
	Environmental impact of the food/ meat during its production	1,572	9.4	501	12.7
	Price	3,150	18.8	792	20.1
	Quality of the meat (taste, juiciness, tenderness) …	2,884	17.2	624	15.9
	Appearance of the meat (e.g., its color, freshness)	2,220	13.3	483	12.3
Would you accept Artificial Meat as a viable alternative to normal meat in the future (Just like other meat substitutes like Soy proteins)?	Yes, I already eat meat substitutes or meat alternatives	837	15.3	278	25.1
	Yes, but I do not eat meat substitutes or meat alternatives	1,579	28.8	371	33.4
	No, but I eat meat and/or meat alternatives	1,804	32.9	286	25.7
	No, I do not eat meat substitutes and/or meat alternatives	1,265	23.1	176	15.8
Which of the following reasons would be most likely to persuade you to try Artificial meat?[a]	As a solution to feed the ever-growing human population	1,647	12.2	445	14.4
	It has more attractive pricing than conventional meat	1,646	12.2	509	16.4
	Ethics – it improves the wellbeing of animals and reduces animal slaughter	1,861	13.8	535	17.3
	Less risk of Zoonosis (disease that can be transmitted from animals to people, e.g., Foot & mouth disease)	1,630	12.1	462	14.9
	Attractiveness of high-tech technologies	1,371	10.1	330	10.6
	Curiosity	1,584	11.7	260	8.4

(Continued)

TABLE 3 (Continued)

Question	Response options	Survey 1 and 2 (n=11,013)		Survey 3 (n=1,111)	
		Number of responses	Percentages (%)	Number of responses	Percentages (%)
And which of the following would be the most likely reasons why you would not be willing to try Artificial meat?[a]	It is unnatural	1,756	12.7	47	20.0
	It is less tasty/appealing	1,587	11.4	15	6.4
	I am worried about its safety	1,929	13.9	29	12.3
	It is more expensive than normal meat	1,667	12.0	15	6.4
	I am reluctant (feel disgusted/ nervous)	1,584	11.4	22	9.4
	It has a negative impact on local farmers	1,546	11.2	22	9.4
	Negative impact on local farmers & their jobs	1,426	10.3	28	11.9
	I do not trust laboratories and artificial meat start-up companies	966	7.0	37	15.7
Which of the following statements would you associate with Artificial meat?[a]	Adequate nutrition	1,241	9.0	468	13.5
	Tasty /tastes similar to real/normal meat	1,527	9.2	497	14.3
	Safety	1,923	14.0	626	18.1
	Less as a solution to feed the ever-growing human population	1,548	11.3	452	13.0
	It is less expensive or has better pricing than conventional meat	1,354	9.9	406	11.7
	It has a smaller environmental footprint	1,267	9.2	327	9.4
	Leads to the reduction of farming	1,161	8.5	264	7.6
	Leads to no farming	1,038	7.6	218	6.3
In which of the following cases would you be most likely to eat Artificial meat regularly?	At the restaurant	1,323	23.9	462	29.3
	At home	1,431	25.9	474	30.0
	In prepackaged ready-to-eat meals (e.g., lasagna…)	1,101	19.9	372	23.6
	I do not want to eat artificial meat regularly	821	14.8	141	8.9
	Other	852	15.4	129	8.2

(Continued)

and age, country and income, country and education, gender and income and education and income (Table 1).

South Africa came out as the country that was the most willing to try "artificial meat" while Ghana was the least willing to do so (Figure 4).

Those most willing to try were aged between 31 and 50 and had revenue less than $1,500 (data not shown). Respondents with a technical education were more willing to try (Figure 4).

Willingness to eat (WTE) regularly

Most respondents were willing to eat "artificial meat" on a regular basis (85.3%) in survey 2 as well as in survey 3 (87.22%).

In survey 3, WTE was also significantly affected by the perceived impacts of conventional meat on livestock ($p < 0.0001$), rural life ($p < 0.0001$), the environment ($p < 0.006$), ethics ($p < 0.002$) as well as the frequency of meat consumption ($p < 0.004$).

The pooled data for the 5 countries in common between survey 2 and 3 showed that WTE significantly according to country and age (Figure 5; Table 2). Interactions were significant between country and age, country and gender, country and income, country and education and education and income (Table 2).

Kenya was the most willing to eat "artificial meat" but did not differ significantly from South Africa and Cameroon (Figure 5).

Those most willing to eat were over 51 years of age but did differ significantly from respondents aged 31–50. WTE was higher for males with higher incomes and for females with low incomes ($3,000–4,000 and $4,000 or more and $1,500 or more for females). These 3 groups did not differ significantly. Respondents with a technical education were more willing to try.

Willingness to pay (WTP)

In survey 2, 60.7% of respondents were willing to pay less than for conventional meat (36.4% were willing to pay less and 24.3% were willing to pay much less than for conventional meat) while 12.7% were willing to pay more (8.6% more and 4.1% much more than for conventional meat) and 26.7% were willing to pay the same price as for conventional meat.

The same pattern was observed in survey 3, 70.0% of the respondents were willing to pay less than for conventional meat (36.4% were willing to pay less and 33.6% were willing to pay much less than for conventional meat) while 10.9% were willing to pay more (7.9% more and 3.0% much more than for conventional meat) while 19.1% were willing to pay the same price as for conventional meat.

Pooled results of the two surveys are indicated in Figure 6.

In survey 3, WTP was also significantly affected by the perceived impacts of conventional meat on livestock, rural life, the environment, ethics ($p < 0.0001$) as well as the frequency of meat consumption ($p = 0.004$).

Analyses of the data pool for 5 countries in common between survey 2 and 3 showed that WTP differed significantly according to country and education (Figure 7; Table 3). Interactions were significant between country and age, country and income, and education and income (Table 3).

The country that was the most willing to pay was South Africa and the least willing to pay was Kenya (Figure 7).

TABLE 3 (Continued)

Question	Response options	Survey 1 and 2 (n=11,013)		Survey 3 (n=1,111)	
		Number of responses	Percentages (%)	Number of responses	Percentages (%)
Now that you have learnt a little bit more about Artificial meat, what do you think about it?	It is promising and / or acceptable	1,257	22.7	437	39.3
	It is fun and/or intriguing	3,262	59	497	44.7
	It is absurd and/or disgusting	1,009	18.2	177	15.9
Artificial meat is already available in some countries, when do you think artificial meat will be widely accepted?	In the short term – 1 to 5 years	1,208	21.8	408	36,7
	In the medium term—6 to 15 years	2,381	43.0	345	31.0
	In the long term—more than 16 years	1,124	20.3	261	23.5
	Never	815	14.7	97	8.7

[a]Only major answers are indicated.

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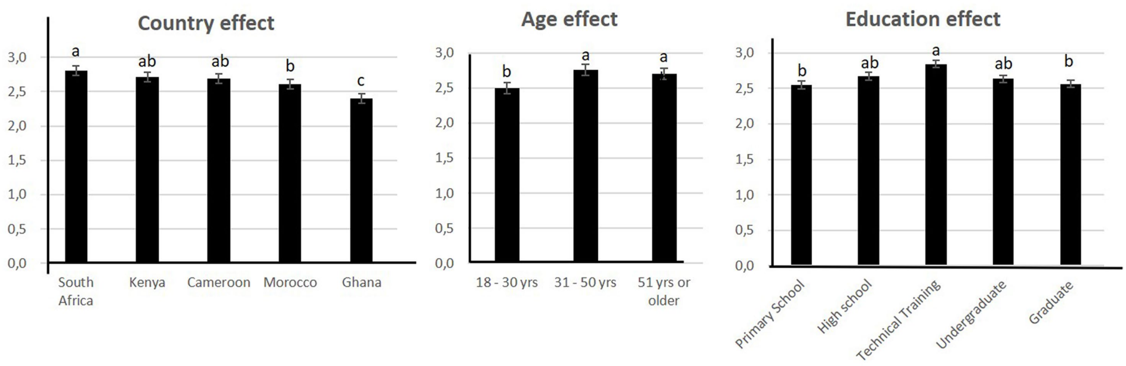

FIGURE 4
Significant factors affecting willingness to try "artificial meat."

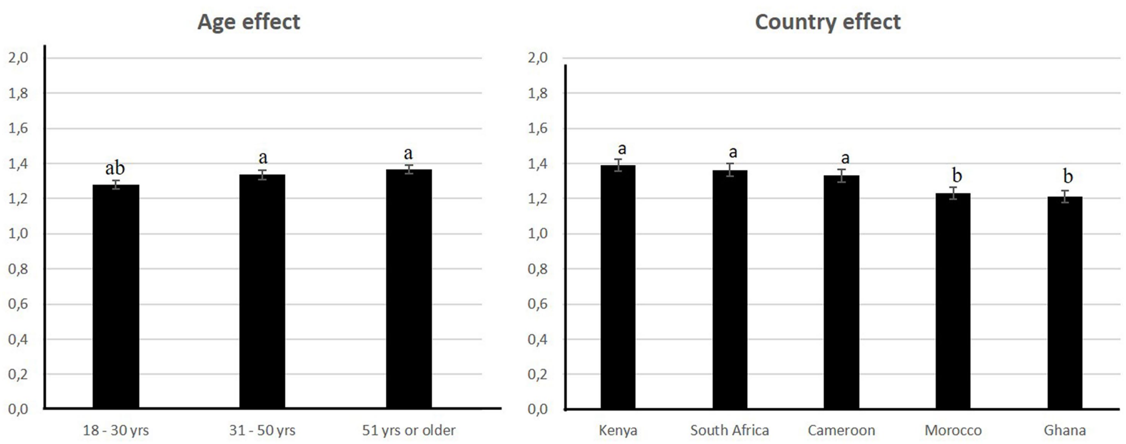

FIGURE 5
Significant factors affecting the willingness to eat "artificial meat."

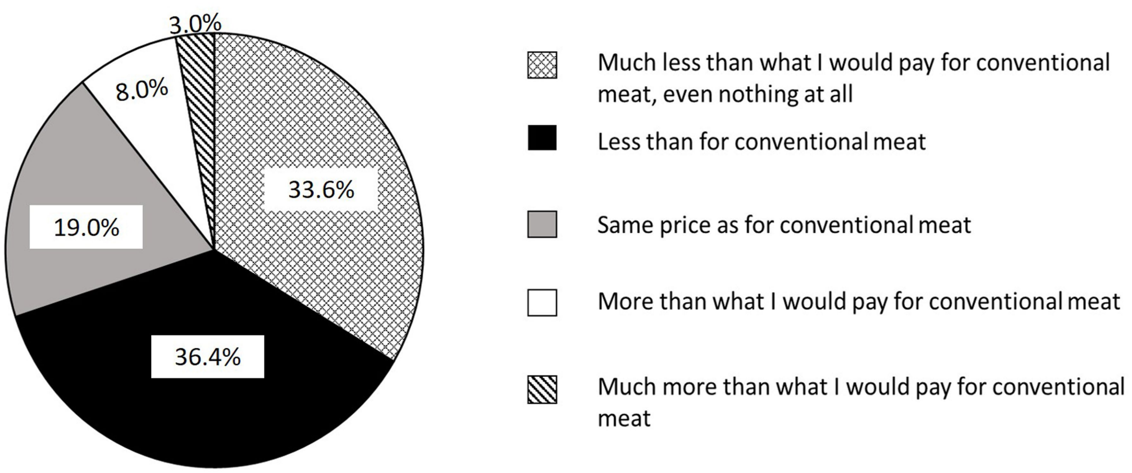

FIGURE 6
Percentages for willingness to pay for "artificial meat".

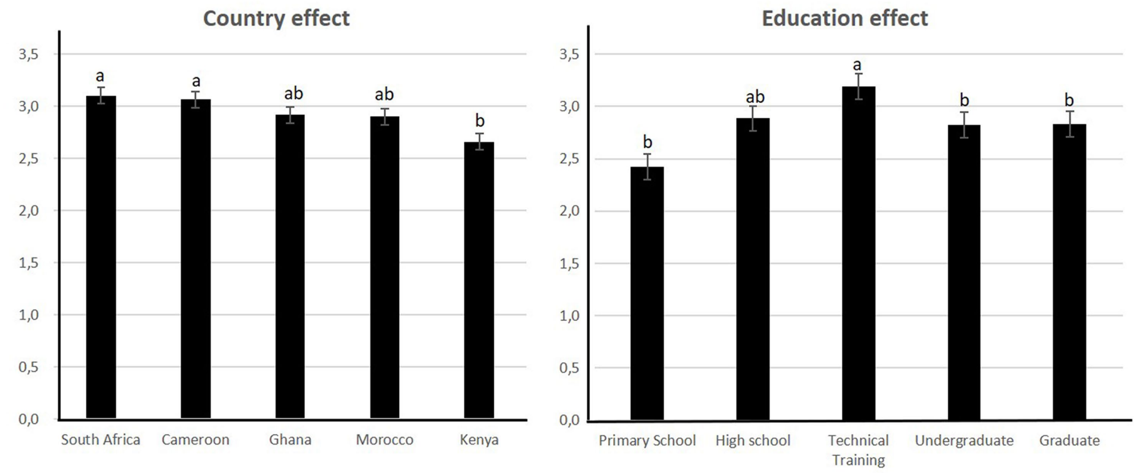

FIGURE 7
Significant factors affecting the willingness to pay for "artificial meat."

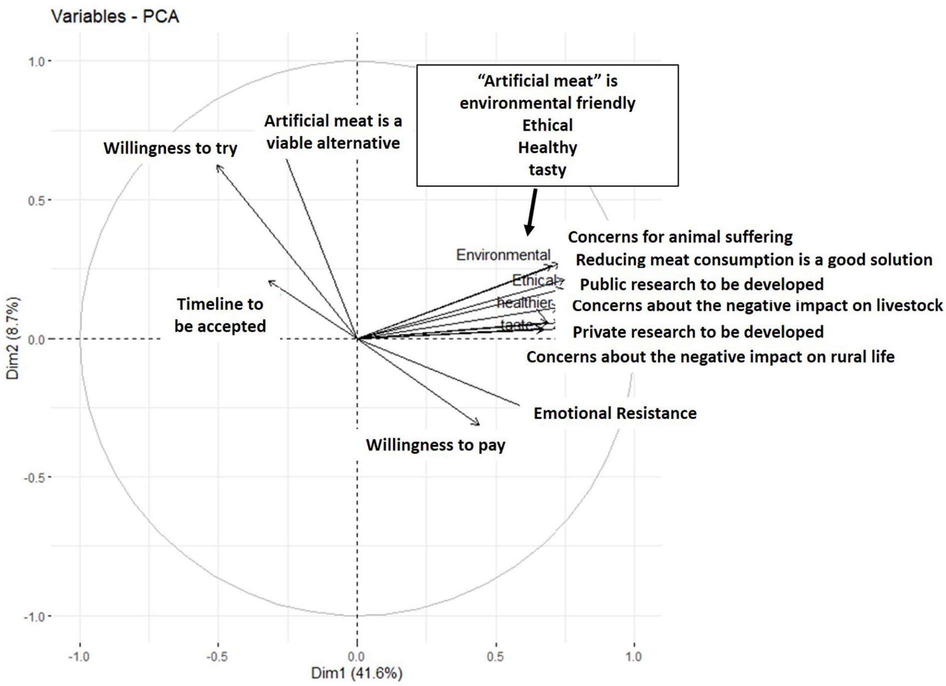

FIGURE 8
Principal Component Analysis of the main quantitative variables studied in survey 3.

Potential drivers of acceptance of "artificial meat"

A PCA was performed to investigate the underlying motives and barriers to acceptance of "artificial meat" by respondents, with all quantitative variables of survey 3 for which all responses from the same respondents were available (Figure 8) (12 questions).

The PCA revealed 2 groups of correlated variables on either side of the vertical axis. WTT was positively correlated with "artificial meat" perceived as a viable alternative to meat and its perceived timeline for availability. WTP was positively correlated with societal challenges (concerns about the ethics and environmental problems caused by on-farm breeding, animal suffering, impact on rural life and livestock) and negatively correlated with emotional resistance.

In this analysis, WTE was negatively correlated with WTT (r = −0.40; $p < 0.001$) but very slightly correlated to WTP (r = 0.04; $p < 0.05$). WTT was negatively correlated to WTP (r = −0.30; $p < 0.001$). Emotional resistance was negatively correlated with WTT (r = −0.50; $p < 0.001$) but positively correlated with WTE and WTP (r = 0.30 for both; $p < 0.001$).

Discussion

What factors will affect the acceptance of "artificial meat" across Africa?

The acceptance of "artificial meat" depends on several factors such as age, income and education.

Contrary to other studies which evidenced a gender effect (23–25, 31), in this study, gender did not have an effect on the acceptance (WTE & WTT) of "artificial meat," as argued by other studies that did not find an association between gender and food neophobia (32–34). This contradiction could be explained by the fact that our survey was not fully representative of the African population in terms of urban and rural populations, with 58% of Sub-Saharan Africa being rural and only about 30% in North Africa (35, 36). In addition, in previous surveys, different interactions of the effect of gender with other effects have been observed, which explains why the effect of gender is not consistent (23, 37).

According to the PCA, WTP could be associated with positive acceptance of "artificial meat." WTT was negatively correlated with WTP and WTE. This result is counterintuitive as one would expect WTT to be a precursor to WTE. This result may indicate that WTT may have different motives from WTP and WTE. The main motive for WTT would be curiosity (19), while WTP and WTE are motivated by ethics and environmental issues related to livestock, as well as price, as discussed below. This has also been observed in other studies that like in Taiwan where consumers are willing to buy plant-based meat alternatives for sustainable development of the environment despite their high prices. This study concluded that consumers' perception of green value will affect their attitude toward green products (38, 39). It was also suggested that that consumers who are highly concerned about animal welfare and environmental issues are likely to consider livestock meat production as causing more ethical and environmental problems than their counterparts, which may affect negatively their consumption of meat or positively their consumption of meat alternatives (40).

Other factors that have affected African consumers' perspective on "artificial meat" are also discussed.

Age

Age was the most important factor in our study. Other studies have shown that "artificial meat" is more attractive to younger respondents in France, Brazil and Germany (19, 23, 41). In our study, older respondents (>30 years) were the most willing to accept (WTT & WTE) "artificial meat" but age had no influence on WTP. This is in line with results in China where young respondents had the lowest WTT (25). This is also in line with the Australian survey of the Generation Z (18–24 years of age) who feared betraying Australia as a meat-eating nation (42). In Africa, livestock entrepreneurship is a self-employment option where unemployment rates are still high for younger populations (43). However, these results can be mitigated because our survey did not represent younger respondents very well. Indeed, 40% of the African population is under 15 years of age (44) and this age group was not included in the survey.

Country

Our survey suggests that although there is a general positive outlook on "artificial meat," the extent of this potential acceptance is not the same in all countries. This indicates the diversity of African consumers in terms of food behavior, income, gender, age and education, as all of these differ in these countries. In our study, consumers from South Africa were the most willing to try and pay for "artificial meat," with no difference to Kenyan consumers who were the most willing to eat. In a previous study that surveyed 10 countries, South Africa was shown to have a high level of acceptance of "artificial meat," second only to Mexico (21). The suggested reason by this study was that South Africa has been influenced from other countries such as UK or the Netherlands. This observation may also be due to the various migrants in the country. Indeed, South Africa has the highest number of migrants in its population, followed by Kenya, Cameroon, Ghana and Morocco (45, 46). The fact that Ghana and Morocco have the least migrant populations could explain why they are the least accepting of "artificial meat."

These countries with a higher percentage of migrant population are therefore more open to novel foods and will consequently have higher levels of acceptance of "artificial meat." South Africa differs from a number of other African countries due to the strong influence of European cuisine (21). The migrant population from other countries may differ between South Africa and other African countries. Indeed, African immigration is mostly characterized by movements within the continent (47), with the exception of South Africa which has had a more western migrant population compared to other African countries (21).

Added to this, South Africa is home to the first company to produce "artificial meat" on the African continent and this company has been funded by overseas investors as well as South Africans themselves. Kenya appears to be the country the most willing to eat "artificial meat" due to its forefront position in relation to drought (48).

Otherwise, Kenya is currently losing its livestock due to drought and may perceive "artificial meat" as a source of relief for its meat consumption but is less willing to pay for "artificial meat." Ghana appears to be less willing to accept "artificial meat." "Artificial meat" companies must therefore have a country-specific strategy, targeting those with similar demographics and food consumption habits.

Income

Income as well as purchasing power in Africa are increasing, but despite this, respondents are still willing to pay less for "artificial meat" than for meat. In the pooled data, most respondents had a monthly income of more than USD 1,500 (43.56% < USD 1,500 and 53.44% > USD 1,500). The average salary in Africa is approximately USD 758 with great variability between countries (49–51) but the price of beef is much lower than in European countries, which means that purchasing power should be adjusted accordingly. The price of beef in the countries surveyed varies from USD 4 to USD 13 (52). The African Development Bank (AfDB) classification measures the middle class as people living on an income of between USD 2 and 20 per person per day, or USD 60 and USD 600 per month (2011) (53). This difference between countries was also reflected by the interaction effect between income and country in the ANOVA model.

Therefore, with this information, our survey only discriminated between rich and non-rich people. Despite this limitation, this can be considered as an indication that the WTP for "artificial meat "of African countries might be very low and, in any case, lower than for conventional meat.

This could lead to the conclusion that "artificial meat" will not be considered a premium product. A report from the consulting firm Mckinsey (54) indicated that "artificial meat" will initially bear a premium price tag, therefore putting it out of reach of some consumers, especially African consumers. Prices are likely to fall as the industry scales up, therefore pushing it on the spectrum of the long term (55). Most respondents consider "artificial meat" will be available in the medium term (6–15 years), as do the French (40.6%) and the Chinese (45.1%) respondents, but different from Brazil where 38.9% of respondents consider that "artificial meat" will be available in the long term (> 15 years).

Education

The literature has shown that education is a predictor of "artificial meat" acceptance since this product is more appealing to more educated consumers (56–58). Those with lower levels of education are more likely to have food neophobia (59). There has been an increase in the education level in Africa (60) but despite this increase, inequalities are still a critical issue (61). On average, only 9% of Africans were indeed enrolled in post-secondary education in 2019 (62) compared to 73% in Europe (62). In the cities of countries studied in this work, these proportions are 14% in Cameroon, 10% in Kenya, 17% in Ghana, 24% South Africa and 41% in Morocco. The respondents of our survey therefore represent only a minority of actual African citizens, as most of them have higher education.

Our survey showed that "artificial meat" is more appealing to respondents with a technical background. The reason for this might be that respondents with a technical background are more open to technological innovations. Our survey did not include non-educated respondents. Some experts believe that meat alternatives will create new job opportunities along the production chain (63–65). Others discussed the possibility of using plant ingredients as culture media instead of bovine serum (64). Some African countries could therefore become a supplier to this industry. On the other hand, these new technologies will require more trained and qualified staff. Education will therefore play a crucial role in ensuring that "artificial meat" is produced on the African continent. Animal farmers, crop-growing farmers and the rural community are indeed not generally highly educated and may suffer income losses and job losses as a result of the transition to more urban meat production, as they may not be qualified (63).

Education also had an interaction effect with income on WTP and WTE. This is because education is more accessible to those with higher incomes, especially in some developing countries.

Acceptance of "artificial meat"

Most of the respondents in Brazil, France, China (19, 23, 25) and Africa (this study) were willing to pay less for "artificial meat" than for conventional meat but the percentage of African citizens was lower compared to the situation in the other countries (71%, 69%, and 87%, respectively, and 65% for Africa).

Overall, our results show that there may be a positive perspective on "artificial meat" in Africa. However, with the same questionnaire and methodology, WTT was lower than for Brazil, France and China (50%, 51%, and 66%, respectively, *vs* 47.2% on average in Africa) (19, 23, 25) but WTE was much higher (> 80%). This could be due to the fact that African countries found "artificial meat" more fun and/or intriguing than other countries (35%, 23%, and 49%, respectively, and 52% for Africa) (19, 23, 25). It appears that African consumers are keen to adopt "artificial meat" in their diets, and therefore it makes less sense to simply try it.

Interestingly, African and Chinese consumers show less emotional resistance (18.6 and 16.1%) compared to French and Brazilian respondents (55.5% and 32.4%) (23, 25). This may be explained by the fact that African and Chinese consumers are more open-minded and have more diverse dietary habits, such as eating insects (as in Africa) or plant proteins (as in China).

WTT was negatively correlated with WTP and was not associated with prospects for societal changes. This negative correlation suggests that African consumers who are ready to try "artificial meat" may not be willing to pay a high price for this product.

How can "artificial meat" pave its way in a diverse continent?

Africa is vast and diverse. Consumers do not have the same expectations. "artificial meat" industries must therefore have strategies tailored to each country or at least to the five commonly known subregions: North or Northern Africa, West Africa, Central or Middle Africa, East Africa, and Southern Africa.

Price

Africans consider price as the most important factor when it comes to purchasing meat.

Price is considered to be a common negative factor for "artificial meat" (16). This could lead to consumer reluctance if "artificial meat" prices are high. This is why, in both surveys, respondents were willing to pay less than for conventional meat. In order to gain more mainstream recognition, "artificial meat" must be cheaper and possibly produce high quality cuts at a comparatively lower price, as indicated by (66). In practice, price competitiveness is therefore an important factor to take into consideration for African countries at least. Price does not only pose a problem on the consumption side but also on the production side since production costs are still high (67).

Another important point to be considered is how "artificial meat" will be made available to African consumers. Two scenarios can be hypothesized. The first is based on the idea that "artificial meat" would be imported from developed countries, with the exception of South Africa which has already started to produce "artificial meat." The second scenario implies that African countries would have to produce "artificial meat" themselves. Both these scenarios raise certain issues. First of all, it might be more expensive to import "artificial meat" because of its current high price and limited production compared to conventional meat. Secondly, it could be more efficient or less expensive for African governments to implement better policies by helping local farmers rather than building new "artificial meat" industries.

African consumers may be willing to try "artificial meat" because they suppose it will be cheaper than conventional meat, since price is the primary driver in purchasing meat. Even though they are less willing to try "artificial meat," they would be prepared to eat it regularly if the price was affordable. Furthermore, unlike in developed countries, Africans are unsure about the effects of livestock on the environment and ethical issues, which explains why price is by far the most important driver of "artificial meat" acceptance.

Safety

Most African respondents associated "artificial meat" with safety, like Chinese consumers (25). That is, they consider "artificial meat" as a safe product. This is because livestock has been associated with several diseases since in many countries there are no refrigerated facilities to store meat in safe conditions. In Africa, the number of zoonotic disease outbreaks increased between2012 and 2022 (68). The safety of animal-sourced food is therefore becoming a major concern for local populations and policy makers. However, there are still several uncertainties and limited scientific literature on the safety of "artificial meat" (15, 69).

The emphasis on safety may also stem from the 2014–2016 Ebola outbreak and the global COVID-19 pandemic. This pandemic helped raise awareness of the risk of emerging diseases related to animal exploitation. Africans could therefore perceive "artificial meat" as a way to limit these outbreaks in a context of weak health systems. However, there are still some doubts as to the safety of "artificial meat," such as the potential addition of chemicals to the culture medium, resulting in a "chemical" meat with potential negative consequences on consumer acceptance (67, 70). Deregulation of cell lines may also occur (as in cancer cells), which may lead to unknown effects on human health (67).

Contributions and limitations of this work and future research

The answers to the questions in any survey are likely to depend on the wording and sequencing of the questions, which may influence the conclusions of the survey. Many studies have also been conducted by "artificial meat" promoters with clear objectives to influence consumers or accelerate marketing. However, our results could still be relevant to providing useful information for understanding the drivers or barriers to "artificial meat" acceptance by African's rapidly urbanizing citizens. More relevant information could be derived from comparing results obtained with the same experimental design across countries, such as France (19), Brazil (23) and China (25), or across similar social groups (within the same study as in this work). More importantly, relevant studies on "artificial meat" are rare in Africa which makes contextual interpretation difficult.

In addition, there is clearly a strong generational effect, particularly with regard to ethical and environmental issues of livestock production, meat consumption, and therefore the overall perception of meat substitutes, including "artificial meat." Moreover, young, well-educated people are likely to have a clearer idea of the potential and limits of science. All these facts may explain why older people may reject "artificial meat" less as shown in this work, or more, as shown in Germany and France (41), and in Europe (71). Consequently, targeting young, well-educated people as in this survey may better indicate the trends of "artificial meat" acceptance in the future, while underestimating or overestimating this potential acceptance at present.

Generally speaking, opinion surveys must be interpreted appropriately because to their limited representative character. However, this drawback can be partially offset by the consequent size of the sample and the duplication of our survey, which makes it possible to identify the major factors likely to explain, at least in part, the variability in WTT, WTE and WTP for "artificial meat," and to analyze different segments of the population.

Finally, due to the importance of implicit attitudes that are difficult to capture, a recent survey illustrated the inadequacy of relying on self-reported measures when seeking to capture consumer opinions on unfamiliar products such as "artificial meat" (72). However, again, despite these limitations, comparing results obtained with the same experimental design between countries or between similar social groups (within the same study as in this work) is likely to provide useful information.

Conclusion

Meat consumption in Africa is set to increase due to population growth, urbanization and income. This high demand will put pressure on a livestock industry that is not yet efficient in terms of productivity. Despite the small sample sizes of this survey, insights could still be gleaned from the results to get a broad view of the cultured meat perspective in the countries studied. As African countries vary in terms of consumer behavior, culture, tradition and demographics, the potential perception of the challenges facing livestock production and meat consumption is likely to vary accordingly. A strategy must therefore be tailored to each country. Price will be one of the main drivers in acceptance of "artificial meat" by several African countries. Therefore, policy makers, governments and local investors will have to make a choice to direct their financial help towards supporting more efficient meat production in order to meet the increasing demand of meat. Several options could be considered; investing in making livestock production more efficient and sustainable, investing in other animal protein alternatives such as protein from insects which are already widely consumed in many African countries, or investing in the production of meat alternatives such as plant-based meat or "artificial meat." This choice will be reinforced by Africa's limited investment capacity compared to richer countries.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MK: survey, data analysis and draft writing. SC, M-PE-O, JL and J-FH: survey design. J-FH: surpervision. All authors contributed to the article and approved the submitted version.

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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

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2023.1127655/full#supplementary-material

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A comparison of the nutritional profile and nutrient density of commercially available plant-based and dairy yogurts in the United States

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Introduction: Plant-based yogurts are sustainable alternatives to dairy yogurts, but a nutritional comparison of plant-based yogurts within the context of dairy yogurts has not yet been applied to commercially available products in the United States. Dairy yogurts provide significant dietary nutrients, and substituting plant-based yogurts may have unintended nutritional consequences. The objective of this study was to compare the macronutrient and micronutrient values of commercially available plant-based and dairy yogurts launched between 2016 and 2021.

Methods: Nutritional information for yogurts were collected through Mintel Global New Products Database, and products were categorized according to their primary ingredient. Regular-style yogurts (n=612) were included in this study: full-fat dairy (n=159), low and nonfat dairy (n=303), coconut (n=61), almond (n=44), cashew (n=30), and oat (n=15). We utilized the Nutrient Rich Foods (NRF) Index, a comprehensive food guidance system that assigns a score based on the nutrient density of individual foods. This allowed us to compare the nutritional density of the yogurts based on nutrients to encourage (protein, fiber, calcium, iron, potassium, vitamin D) and nutrients to limit (saturated fat, total sugar, sodium).

Results: Compared to dairy yogurts, plant-based yogurts contained significantly less total sugar, less sodium, and more fiber. However, plant-based yogurts contained significantly less protein, calcium, and potassium than dairy yogurts. The yogurts were ranked from the highest to lowest nutrient density based on the NRF Index as follows: almond, oat, low and nonfat dairy, full-fat dairy, cashew, and coconut. Almond yogurts scored significantly higher than all other yogurts, indicating the highest nutrient density.

Discussion: The highest NRF scores were awarded to almond and oat yogurts, likely a result of their low levels of total sugar, sodium, and saturated fat. By applying the NRF model to plant-based and dairy yogurts, we have identified opportunities for the food industry to improve the formulation and nutritional composition of plant-based yogurts. In particular, fortification is an opportunity to improve plant-based yogurt nutritional properties.

KEYWORDS

nutrient composition, nutritional profile, fortification, ingredients, micronutrients, protein, plant-based yogurt, macronutrients

1. Introduction

The world population is rising and is estimated to reach 9.7 billion by 2050 (1). To sustain this growth, the global food supply chain will require a substantial increase in energy and resources (2). However, these resources are impacted by climate change. The effects of climate change are particularly threatening to the livestock industry: rising temperatures can induce heat stress and thus lower productivity and fertility; emerging vector-borne diseases threaten the population; and climate variability affects the availability of crops for feed (3). In addition to the potential uncertainty of available resources due to climate change, the sustainability of the agricultural food supply must be improved (4). The dairy industry is one critical food production sector with a considerable impact on the environment due to greenhouse gas emissions, use of water resources, and large land requirements (5). For example, the global dairy industry was estimated to have emitted 1,711.8 million tons of CO_2 equivalent in 2015, primarily from enteric fermentation and emissions from feed production and manure management (3). European dairy farms have been estimated to contribute to approximately 80% of the total carbon footprint of dairy products (6). Livestock is directly responsible for 38 and 4% of the United States CH_4 and NO_2 emissions, respectively (7). Despite the dairy industry's effect on the environment, global cow milk production has grown approximately 2.8% per year between 2005 and 2015 (3).

In the U.S., approximately 6.3% of all dairy consumed is in the form of yogurt (8). In 2021, consumers spent $9,246 million on yogurts and yogurt drinks (9). In comparison, the plant-based yogurt market is valued at roughly $1,600 million and is expected to grow to more than $6,500 million by 2030 (10). Within this category, plant-based yogurts have been positioned as a more sustainable alternative to dairy yogurt. Further, plant-based yogurt production emits fewer greenhouse gases and requires less land than the production of dairy yogurts (11, 12). Increased environmental consciousness has been identified as a driver for adopting a plant-based diet (13). However, despite the appeal of the environmental benefits of a plant-based diet, this may not translate to consumer motivation to purchase specific products, like plant-based yogurt. A Mintel report (9) found that among American yogurt buyers, fewer than one-half (42%) perceived plant-based yogurt as more environmentally friendly than dairy yogurt. However, "trying to eat healthier" was the primary motivation for anticipated increased household yogurt consumption (9). Therefore, it has been recommended that plant-based yogurt brands specify the health benefits of their products' ingredients to attract consumers (9). This presents a challenge: dairy yogurt is considered a nutrient-rich food that offers high quantities of desirable nutrients and, dependent on the type, relatively low amounts of fat and sugar (14). When developing plant-based yogurts, it is important to consider the overall nutritional profile since consumers may utilize these products as a direct substitute for dairy products.

Previous studies have examined the nutritional properties of commercially available plant-based yogurts in the United Kingdom (15), western United States (16), European Union (17), Norway (18), Greece (19), Ireland (20), and across multiple countries (21). Some plant-based yogurt's nutritional values were found to be significantly different from dairy yogurt's nutritional values. Significantly different macronutrients have included energy (15, 17), fat (15, 17), saturated fat (15, 19), carbohydrates (15, 17, 19), total sugar (15, 19), fiber (15, 18, 19), protein (15, 17–19), and sodium (15, 18, 19). Additionally, some macronutrients within the plant-based yogurt category were found to be significantly different from each other (16, 19). Regarding micronutrients, calcium levels in plant-based yogurts significantly differed from dairy yogurts (15).

It is important to note that only one plant-based yogurt nutrition study examined products from the U.S. market (16). While Craig and Brothers (16) provided important new insights into the comparison within the plant-based yogurt category, there was no formal comparison to dairy yogurt. The present study is the first to compare the nutritional properties of dairy and plant-based yogurts from the U.S. market. Unlike previous studies examining plant-based and dairy yogurts, here we differentiate between the fat levels of the yogurts, whereas previous studies combined full-fat, low-fat, and nonfat yogurt. This separation provides insight into comparing fat and saturated fat levels in dairy yogurts to plant-based yogurts. Additionally, we conducted nutrient profiling to assess the nutrient density of plant-based and dairy yogurt products. This profiling provides a holistic approach, taking into consideration multiple nutrients both that are desirable and those that should be limited. In this study, we utilized the Nutrient Rich Foods (NRF) Index, a comprehensive food guidance system that assigns a score to an individual food based on its nutrient density (22). While several other models have been used to assess the nutrient density of foods, the NRF was recently applied to plant-based milk (23), providing an opportunity to compare plant-based products across product categories. The NRF Index is a nutrient profiling method, and its results can inform the food industry on how products can be reformulated (24). In this regard, the plant-based industry can evaluate how the nutrient density of different plant-based yogurts compares to dairy yogurts.

One way the food industry has attempted to address nutrient deficits is through the fortification of vitamins and minerals. Studies have suggested that fortification can improve the nutrient density of plant-based yogurts (15, 25). While this strategy can be effective at increasing the nutrient content, there is also a growing trend of products with a simple ingredient list (13, 26, 27). This becomes challenging within the plant-based category because additional ingredients are needed to provide functional and sensorial properties that mimic conventional animal products (28). This study will contribute to the growing body of research on the inclusion of gums and starches and the fortification of vitamins and minerals in plant-based yogurts by examining the frequency of these additives based on ingredient lists.

As the plant-based yogurt industry continues to launch new products, the nutritional differences between the variety of plant-based and dairy yogurts must be quantified and understood. The objective of this study is to compare the macronutrient and micronutrient profiles of commercially available plant-based and dairy yogurts in the United States using Mintel Global New Products Database, a market research database. Additionally, the NRF Index is used to compare the overall nutrient density of dairy and plant-based yogurts. This information will help the food industry identify areas of opportunity in the nutritional composition of plant-based yogurts to formulate nutritionally dense products.

2. Methods

Mintel Global New Products Database (GNPD) was used to generate a database of dairy and plant-based yogurts. From henceforth, this paper will refer to yogurt made from cow milk as "dairy." The database contained refrigerated yogurts, both flavored and unflavored, launched in the United States between January 2016 and January 2021.

2.1. Yogurt database

The final database was determined based on the inclusion and exclusion criteria (Figure 1). The database yielded 622 regular-style flavored and unflavored yogurts: 462 dairy and 160 plant-based. Yogurts were categorized according to their primary ingredient, henceforth referred to as the "base." This was achieved through a review of the ingredient list and a supplemental web search of the product descriptions and images. Bases for dairy yogurt included full-fat ($n = 159$), low-fat ($n = 288$), and nonfat ($n = 15$). Low-fat and nonfat yogurts were consolidated into one base type for statistical analysis due to the Food and Drug Administration's (FDA) elimination of separate standards of identity for low-fat and nonfat yogurt in 2021 (29). Bases for plant-based yogurt included coconut ($n = 61$), almond ($n = 44$), cashew ($n = 30$), oat ($n = 15$), soybean ($n = 4$), coconut and cashew blend ($n = 4$), and flaxseed ($n = 2$). Due to their small sample size the following yogurt bases were underpowered to analyze nutrient differences: soybean, coconut and cashew blend, and flaxseed yogurts. As a result, these products were excluded from statistical analysis.

Relevant to the present analyses, information in the final database included product, company name, description, serving size (g), ingredient list, and nutritional content. In the U.S., the Nutrition Facts Label must include the following macronutrients and micronutrients: calories, total fat, saturated fat, trans fat, cholesterol, sodium, total carbohydrate, dietary fiber, total sugars, added sugars, protein, vitamin D, calcium, iron, and potassium (30). Nutritional data in the final database thus included energy (kcal), total fat (g), saturated fat (g), carbohydrate (g), fiber (g), protein (g), total sugar (g), sodium (mg), vitamin D (mcg), calcium (mg), iron (mg), potassium (mg), and vitamin B12 (mcg). Nutrient content reported as <0.1 g or < 5 mg was replaced by 0.1 g and 5 mg in the database, respectively. To account for variable serving sizes, nutrient content for all products was reported in grams, milligrams, or micrograms per 100 grams.

During the product search timeframe, the FDA approved changes to the nutrition facts and daily recommended values, which had important implications in the present analysis. In 2016, the FDA updated the Nutrition Facts label (30). Of relevance to the current analyses, these new requirements included updates to reference values used in the declaration of percent Daily Values (DV) of some nutrients (i.e., fat, total carbohydrate, dietary fiber, sodium, potassium, calcium, and vitamin D) and required declarations of micronutrient amounts (i.e., vitamin D, calcium, iron, and potassium). The first phase of modifications was required on January 1, 2020. Thus, the new Nutritional Facts label updates impacted several aspects of this study's database. See Supplementary Table S1 for description and details on products with new and old nutrition labels and management of nutritional information for the final product database. As a result of these changes that occurred during the timeframe of the product search, some yogurts may be missing one or more nutrients selected for analysis in the present study. Products identified in Mintel GNPD as not reporting one or more nutrients were included in the final database. A researcher performed a manual search to verify nutrients were not reported.

2.2. Nutrient profiling

The Nutrient Rich Foods (NRF) Index is a validated comprehensive food guidance system that assigns a score to an individual food based on its nutrient content in relation to calories (31, 32). The NRF Index's algorithm is based on a positive sub-score for nutrients to encourage (qualifying) and a negative sub-score for nutrients to limit (limiting) (22, 24). The NRF score of an individual food is calculated by the subtraction of the negative sub-score by the positive sub-score. A higher NRF score indicates a higher nutrient density. Previous studies have used different versions of the NRF Index (23, 31, 33, 34), but it has been recommended that for each model the selection of qualifying nutrients be based on nutrients that are beneficial to health (i.e., mainly vitamins and minerals), and limiting nutrients be based on fats, sugars, and sodium (22). In this study, our NRF6.3 model was composed of a positive sub-score for six qualifying nutrients and a negative sub-score for three limiting nutrients. The qualifying nutrients and their reference amounts include protein (50 g), fiber (28 g), calcium (1300 mg), iron (18 mg), potassium (4700 mg), and vitamin D (20 mcg). The limiting nutrients and their reference amounts include saturated fat (20 g), total sugar (50 g) in accordance with previous NRF models (33, 34), and sodium (2300 mg). Each nutrient was expressed as a percentage (%DV) calculated per 100 kcal, where i = qualifying nutrients and j = limiting nutrients (Eq. 1).

$$\text{NRF6.3} = \left(\sum_{i=1}^{6} \frac{\text{Nutrient per 100kcal}}{\text{Daily Value i}} * 100 \right) - \left(\sum_{j=1}^{3} \frac{\text{Nutrient per 100kcal}}{\text{Daily Value j}} * 100 \right) \tag{1}$$

2.3. Additive ingredients

To identify the use of additive ingredients, specifically, gums, starches, vitamins, and minerals, ingredient lists were examined for all products in the final product database. The frequency of each ingredient used in each base was recorded.

2.4. Statistical analysis

Separate one-way analysis of variance (ANOVA) models were used to compare each nutrient variable across the different yogurt bases. Tukey's honestly significant difference (HSD) tests were used to test for significant differences in nutrient values among the yogurt bases. For the NRF Index, separate one-way analysis of variance (ANOVA) models were used to compare each score across

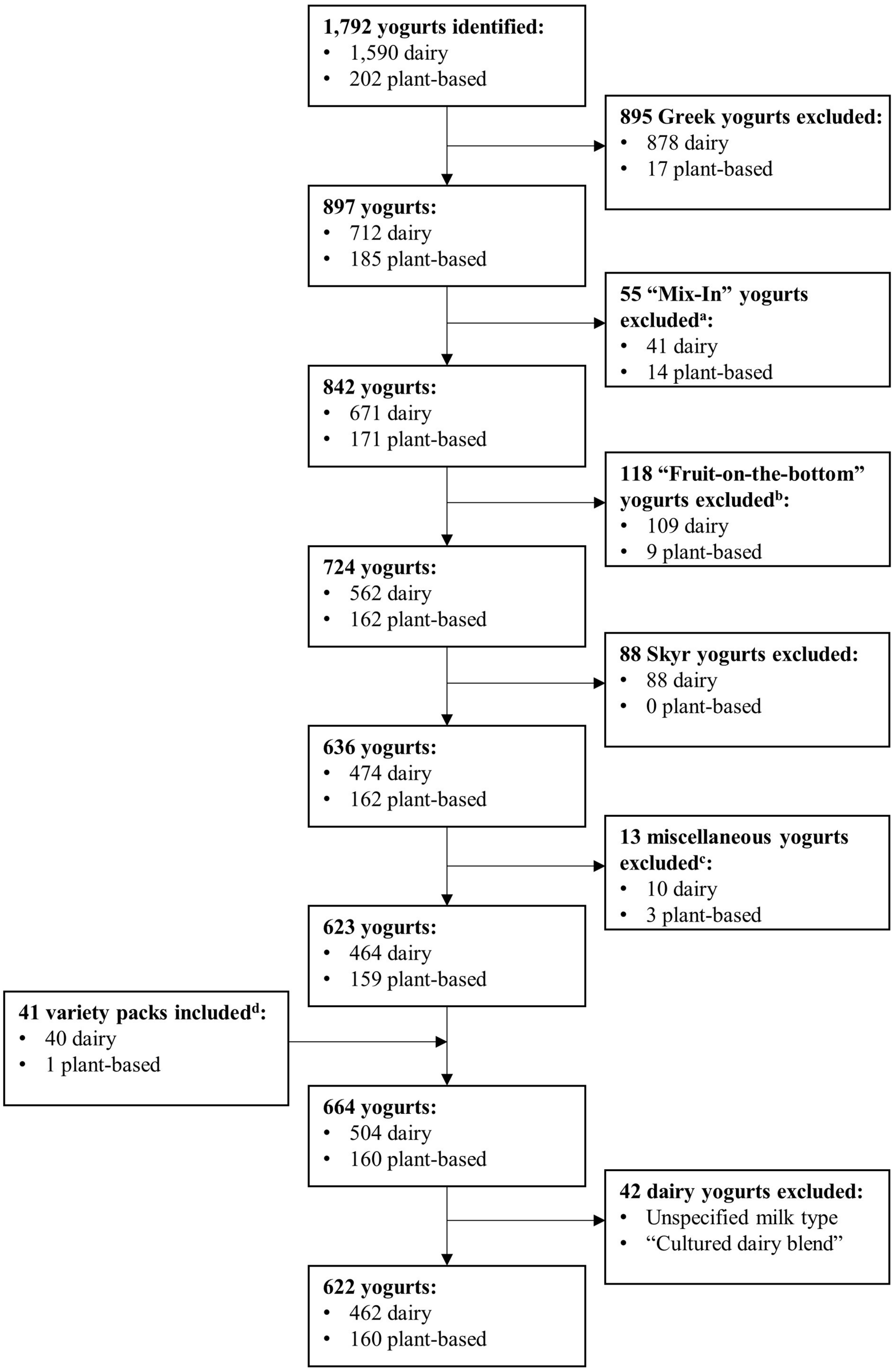

FIGURE 1
Flow diagram visually depicting the creation of the final database showing step by step inclusion and exclusion criteria. [a]Product names and/or descriptions that included "mix," "topping," "crunch," "crisp," "streusel," "piece," "slices," or "granola." [b]Products with ingredient layers or described as "on the bottom." [c]Kefir and products with missing nutrition facts labels. [d]Packages with individual products combined in a secondary packaging (variety packs) were considered separate products.

the different yogurt bases. Tukey's honestly significant difference (HSD) test was used to test for significant differences in macronutrient and NRF6.3 scores among the yogurt bases, at value of $p \leq 0.001$, while $p \leq 0.002$ was considered significant for micronutrient analysis. Statistical analysis was performed in R (version 4.1.2).

3. Results

3.1. Macronutrients

We analyzed the energy, total fat, saturated fat, carbohydrates, fiber, total sugar, and protein content across 6 different yogurt bases (full-fat dairy, low and nonfat dairy, coconut, almond, cashew, and oat). Significant differences ($p \leq 0.001$) among yogurt bases were observed for all macronutrients examined (Figure 2 and Supplementary Table S2). A Tukey HSD post-hoc test was conducted to reveal differences between product categories. The energy (kcal/100 g) of the yogurts in the database ranged from oat yogurts' 64.2 g to coconut yogurts' 114.2 g. For energy density, full-fat dairy contained more calories per 100 g compared to low and nonfat dairy yogurt. For plant-based yogurts, coconut contained significantly more calories than both dairy groups. Oat yogurt contained significantly fewer calories than full-fat dairy but was not different than the low and nonfat dairy group. Almond and cashew plant-based yogurts were not significantly different from full-fat dairy but were significantly higher than low and nonfat dairy yogurts.

Total fat content was significantly different across product groups. The low and nonfat dairy yogurts and oat yogurts contained the lowest amount of total fat. Coconut and almond yogurts contained significantly more total fat, and full-fat dairy and cashew contained an intermediate amount of total fat. Coconut yogurts contained significantly more saturated fat, followed by full-fat dairy yogurts. There was no difference in saturated fat content among low and nonfat dairy, almond, cashew, and oat yogurts.

For carbohydrate content, we observed the least amount of difference compared to other macronutrients. Low and nonfat yogurts contained significantly more carbohydrates than full-fat dairy. Coconut and almond yogurts were not significantly different from full-fat dairy, and cashew and oat yogurts were not significantly different from either dairy yogurt category. In other words, we observed no significant difference in carbohydrate content among the four categories of plant-based yogurts, which were not different from the full-fat dairy yogurts.

The average protein content for dairy yogurts was roughly 4.2 g per 100 g. There was no difference in protein content between full-fat and low and nonfat dairy yogurts. In comparing plant-based yogurts to dairy yogurts, almond yogurts were found to have a similar protein content as full-fat dairy yogurts but were significantly less than low and nonfat dairy. All other plant-based yogurts contained significantly less protein, with coconut containing significantly less protein than all other products (approximately 1.2 g per 100 g).

The average total sugar content across all product groups ranged from approximately 5 g to almost 10 g per 100 g. There was no

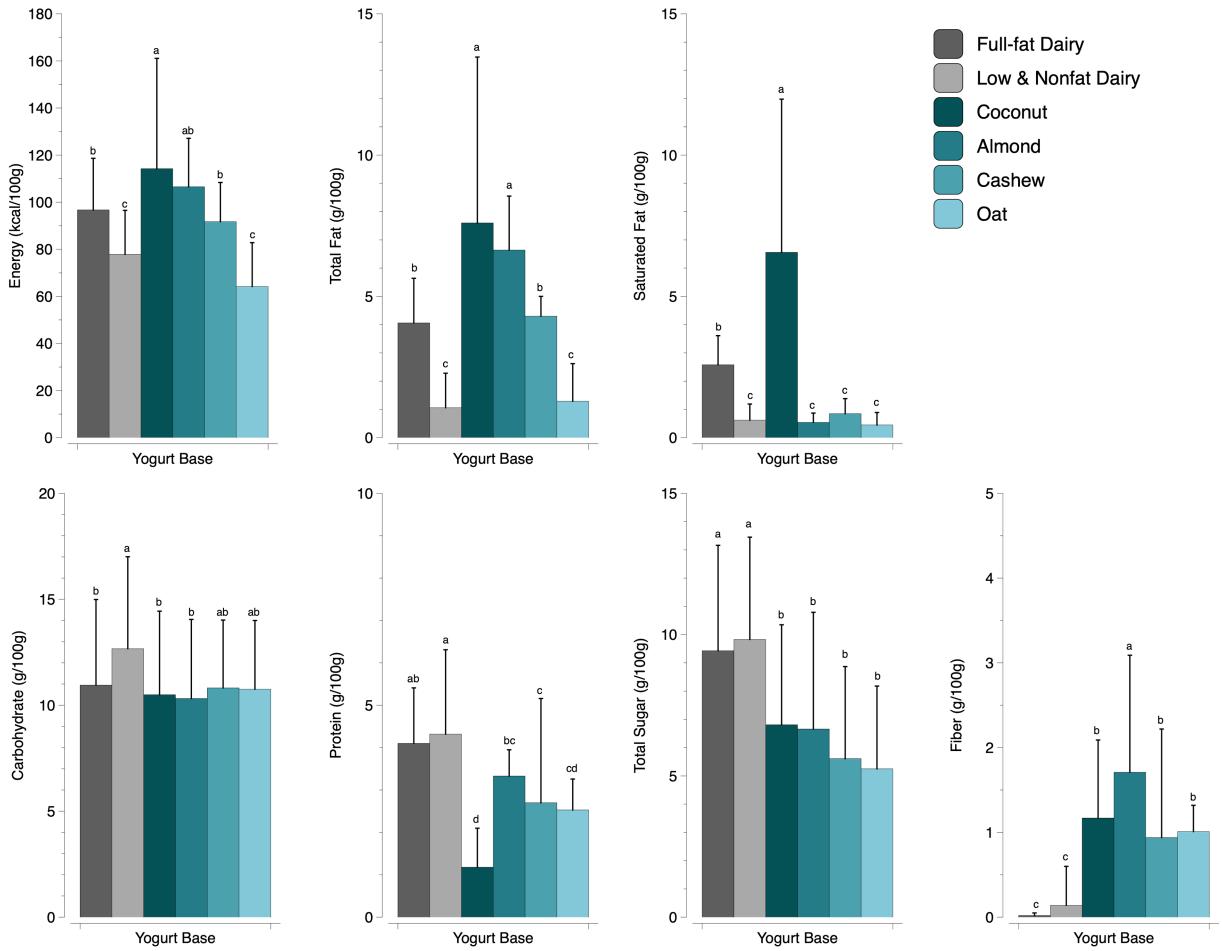

FIGURE 2
A comparison of macronutrients by yogurt base ($p \leq 0.001$; values are reported as mean+SD). Different letters within a macronutrient indicate significant differences between yogurt bases. For every macronutrient, we analyzed full-fat dairy (n=159), low and nonfat dairy (n=303), coconut (n=61), almond (n=44), cashew (n=30), and oat (n=15) yogurts.

difference in sugar content among plant-based products (5.3 g to 6.8 g per 100 g), but they contained significantly less sugar compared to both dairy yogurt groups. There was no significant difference in sugar content among dairy yogurts (9.4g per 100g for full-fat and 9.3g per 100g for low and nonfat).

Almond yogurts contained the highest amount of fiber, which was significantly different from all other yogurt bases. Dairy yogurts contained the least amount of fiber, which was significantly different from all plant-based yogurts (less than 1.2 g per 100 g). Coconut, cashew, and oat yogurts contained intermediate fiber values.

3.2. Micronutrients

Analysis of variance was conducted for the following micronutrients: sodium, potassium, calcium, vitamin D, vitamin B12, and iron across 6 yogurt bases (full-fat dairy, low and nonfat dairy, coconut, almond, cashew, and oat). It is important to note that potassium and vitamin D were not required to report on the Nutrition Facts Label before the FDA's label update. Additionally, vitamin B12 is currently not required to report. Significant differences ($p \leq 0.002$) among yogurt bases were observed for all micronutrients examined (Figure 3 and Supplementary Table S1). There were significant differences in the sodium content across yogurt bases. Full-fat (52 mg per 100 g) and low and nonfat dairy yogurts (53 mg per 100 g) contained significantly more sodium than all plant-based yogurts. Almond, cashew, and oat yogurts contained significantly less sodium than coconut yogurts. Coconut yogurts contained sodium levels significantly different than all other product categories. Full-fat and low and nonfat dairy yogurts contained significantly more potassium, except for cashew, which was not significantly different from low and nonfat dairy yogurts. Coconut, almond, and oat yogurts contained significantly less potassium. Both dairy yogurt bases contained no difference in the amount of calcium, which was significantly higher than plant-based yogurts. Coconut contained the most amount of calcium among the plant-based yogurts, which was significantly higher than almond, cashew, and oat. There were significant differences in vitamin D content between full-fat and low and nonfat dairy yogurts; however, there were no significant differences between plant-based yogurts. Only 35 yogurts reported vitamin B12 content; these yogurts included full-fat dairy, low and nonfat dairy, oat, and coconut. No products within the almond or cashew groups reported vitamin B12 content. Coconut contained the highest amount of vitamin B12 but was not statistically different from full-fat dairy or oat yogurt. Low and nonfat dairy contained the least amount of vitamin B12 but was not statistically different from full-fat dairy yogurt. Coconut, almond, and cashew yogurts contained significantly more iron than dairy yogurts and oat yogurts.

3.3. Nutrient profiling of dairy and plant-based yogurts

For our NRF6.3 model, the following nutrients had to be reported on the product's label to calculate the NRF score: protein, fiber, calcium, iron, potassium, vitamin D, saturated fat, total sugar, and sodium. Of the 612 yogurts included in this study's final database, 275 were removed from the NRF model calculations because products did not report one or more nutrient values required for the NRF calculation (See Table 1 for the number of products in each yogurt base). The remaining 337 yogurts were assigned an average score based on their nutrient density (Table 1). NRF6.3 scores ranged from −22.26 to 15.21, and from highest to lowest were almond, oat, dairy low and nonfat, dairy full-fat, cashew, and coconut. A significant difference ($p \leq 0.001$) was observed for the NRF scores across yogurt bases. Almond yogurts had a significantly higher score than all other yogurts except for oat yogurts. Coconut yogurts had a significantly lower score than all other yogurts except cashew yogurts. Mean NRF6.3 scores in relation to the mean energy density of each yogurt base were mapped (Figure 4). Coconut yogurts had the highest energy density and lowest NRF6.3 score. Oat yogurts had the lowest energy density and the second highest NRF6.3 score.

3.4. Additive ingredients in dairy and plant-based yogurts

Examining ingredient statements revealed a variety of gums and starches used in this study's dairy and plant-based yogurts. The frequency of the gum and starch is reported in each product base (Table 2). Yogurts may have contained a combination of multiple gums and starches. Approximately 88.7% of plant-based yogurts and 64.9% of dairy yogurts contained at least one gum. Alternatively, only 17 of the 150 (11.3%) plant-based yogurts did not contain any gums; these yogurts were all coconut yogurts except for one almond yogurt. The most used gum across all yogurts was pectin, present in 308 of the 612 yogurts (50.3%). 67 (14.5%) dairy yogurts contained carrageenan, but this gum was absent in all plant-based yogurts. Corn starch was present in 199 (32.5%) of all yogurts. Both potato and rice starch were used in some plant-based yogurts but were absent in dairy yogurts. Tapioca/cassava starch was used most often in plant-based yogurts, and a majority of cashew and almond yogurts contained this starch.

Additionally, a variety of vitamins and minerals were additive ingredients present in this study's dairy and plant-based yogurts (Table 3). The addition of calcium salts was more common in plant-based yogurts than dairy yogurts, with 36.7% of plant-based yogurts fortified with calcium while 22.9% of dairy yogurts were enriched with calcium. Calcium citrate and tricalcium/calcium phosphate were most used for both dairy and plant-based yogurts. Vitamin B12 was not present in any dairy yogurts but was used in 41.0% of coconut yogurts. 234 (50.6%) dairy yogurts were enriched with vitamin D3. Vitamin D2 was the most used form of vitamin D in plant-based yogurts. Vitamin E was present in only 3 (5%) coconut yogurts and 4 (1%) low and nonfat yogurts.

4. Discussion

Our findings are consistent with prior work, which demonstrates significant nutritional differences between dairy and plant-based yogurts (15, 17, 18). Despite the growing popularity of plant-based dairy alternatives, the plant-based yogurt category contains variable nutritional compositions in comparison to dairy yogurt. There is an opportunity for the plant-based industry to formulate yogurts that are more nutritionally similar to dairy yogurts. We observed that these nutritional differences in plant-based yogurts are partly due to the use of a variety of ingredients, which help to deliver desirable sensory and textural properties.

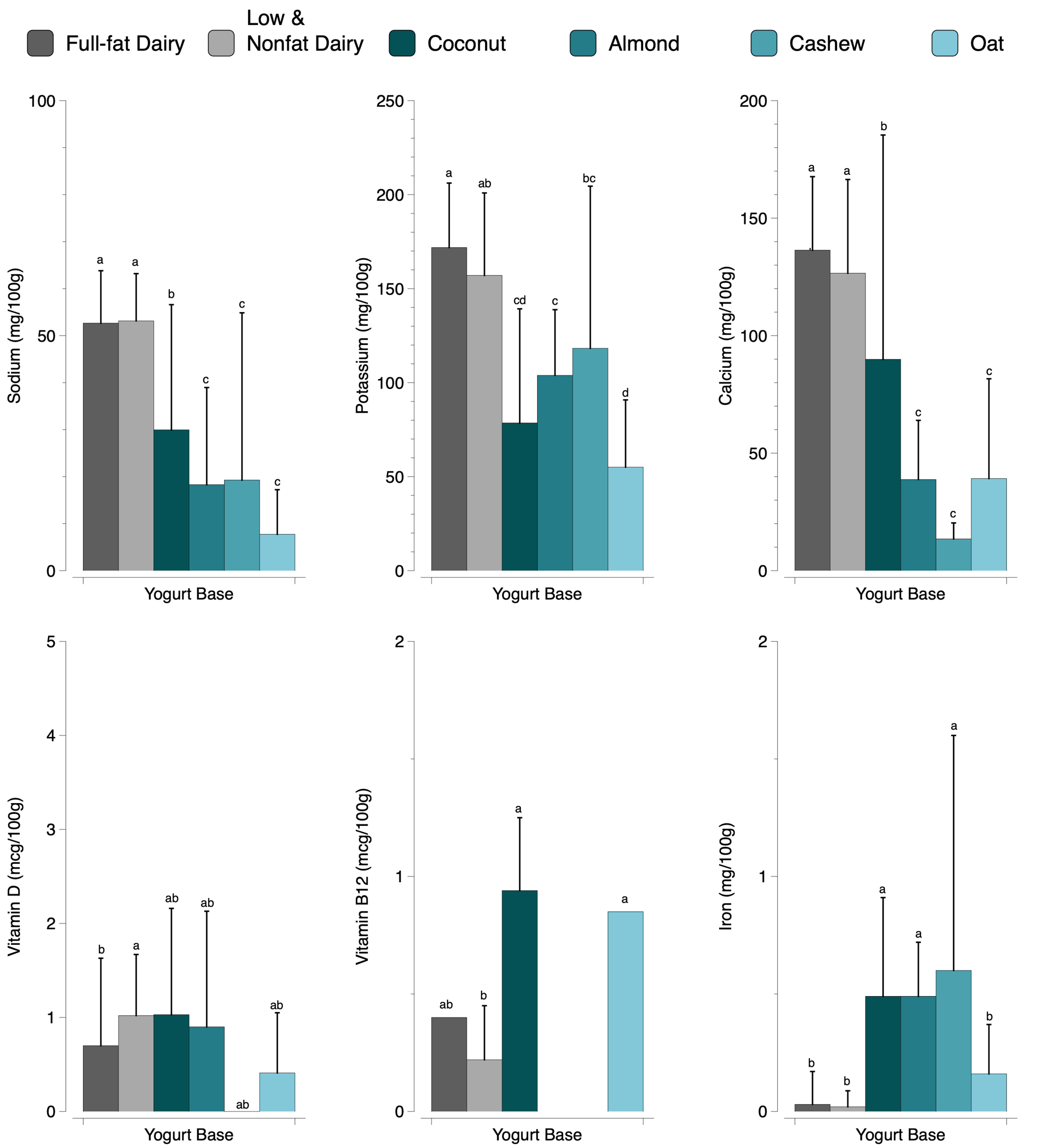

FIGURE 3
A comparison of micronutrients by yogurt base ($p \leq 0.002$; values are reported as mean+SD). Different letters within a micronutrient indicate significant differences between yogurt bases. Some products did not report all micronutrients. The following bases (full-fat dairy, low and nonfat dairy, coconut, almond, cashew, and oat, respectively) reported sodium (159, 303, 61, 44, 30, 15); potassium (94, 213, 31, 27, 11, 15); calcium (159, 303, 60, 44, 30, 15); vitamin D (79, 258, 36, 36, 4, 13); vitamin B12 (1, 5, 25, 0, 0, 4); and iron (159, 303, 60, 44, 30, 14).

4.1. Macronutrients

Six studies and one review have previously examined or analyzed the nutritional properties of plant-based yogurts (15–21). In three of the five studies (15, 16, 19–21) that examined nutritional differences between plant-based yogurt bases, coconut yogurts contained the highest number of calories (15, 16, 21). Our results are in line with Clegg and colleagues (15), as coconut yogurts were determined to contain significantly more calories than dairy yogurts.

Previous studies comparing the nutritional composition of dairy and plant-based yogurt consolidated full-fat, low, and nonfat dairy yogurt into one dairy category. As a result, this limited the understanding of how plant-based yogurts compare with dairy yogurts. The present study separated full-fat from low and nonfat dairy yogurts, which resulted in the identification of significant differences in the fat content. For example, coconut yogurts contained significantly higher fat and saturated fat levels than both full-fat and low and nonfat yogurts. On the other hand, low and nonfat yogurts were most similar in saturated fat levels to almond, cashew, and oat yogurts. Coconut yogurts contained significantly higher fat and saturated fat levels than both full-fat and low and nonfat yogurts. This study demonstrates that combining dairy products with varying fat levels into a single category increases the variability within the category and could mask nutritional differences when comparing them to plant-based alternatives (15, 17–19).

In terms of carbohydrates, low and non-fat dairy yogurts contained the highest carbohydrate levels but were not significantly different from cashew and oat yogurts. This contrasts with a previous study, which reported coconut yogurt to have a significantly higher amount of carbohydrates than dairy yogurt (15). Here, almond yogurts contained significantly higher fiber levels than all other yogurts, which supports findings from a previous study (16). Similar to other studies, dairy yogurt fiber levels were significantly lower than plant-based yogurts (18, 19).

Total sugar in all plant-based yogurts was found to be significantly less than full-fat and low and nonfat dairy yogurts. In comparison to previous studies, total sugar results were variable across yogurt products. For studies that compared all dairy yogurts to all plant-based yogurts, the two groups were significantly different in one study (19) which contrasts with two other studies that reported no difference (17, 18). Clegg and colleagues (15) differentiated between plant-based yogurts and found nut-based (i.e., cashew or almond) yogurts to have significantly less total sugar than dairy, coconut, and soy yogurts. The sweetness of plant-based yogurt may provide an important role in masking unpleasant sensory attributes of plant proteins (35). Ingredients such as fruit purees, syrups, and sweeteners may be added (36) to increase the sensorial acceptance of commercial plant-based yogurts. Interestingly, there was no difference in sugar content among plant-based yogurts nor among dairy yogurts. The average sugar content of all plant-based yogurts was approximately 6 g per 100 g while the average sugar content for dairy yogurts was approximately 9.5 g per 100 g. Therefore, plant-based products may provide advantages over dairy yogurts when considering the sugar content.

All studies that compared plant-based yogurts to dairy yogurt found protein levels to be significantly different (15, 17–19). Dairy yogurts contained the highest protein content, except in one review that reported the average protein in soy yogurts to be higher (21). In the present study, low and nonfat dairy yogurts contained significantly higher protein levels than all other yogurts. Additionally, plant-based proteins do not meet the definition of a complete protein because they are missing essential amino acids. To address this limitation, one strategy is to create hybrid or blended products that combine dairy and plant protein. The incorporation of animal protein would help to

TABLE 1 A comparison of NRF6.3 scores by yogurt base ($p \leq 0.001$; values are reported as mean±SD).

Base	n	Mean±SD
Almond	27	15.21 ± 14.50[a]
Oat	13	9.95 ± 19.75[ab]
Dairy Low & Nonfat	196	4.79 ± 14.86[b]
Dairy Full-Fat	78	−6.17 ± 10.55[c]
Cashew	4	−7.37 ± 8.48[bcd]
Coconut	19	−22.26 ± 22.00[d]

Different letters within the column indicate significant differences between yogurt bases.

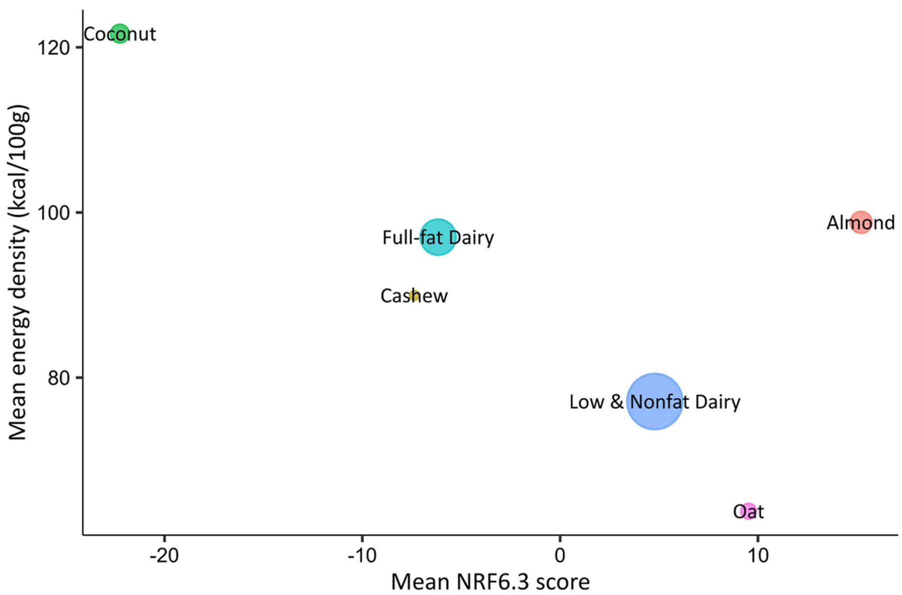

FIGURE 4
Mean NRF 6.3 scores for each yogurt base type shown in relation to energy density (kcal/100g). Higher NRF6.3 scores indicate higher nutrient density per 100kcal. The size of the circle corresponds to the relative number of samples per yogurt base.

TABLE 2 Gums and starches present in dairy and plant-based yogurts.

Function	Ingredient	Dairy n =462		Plant-Based n=150			
		Full-Fat (n =159)	Low & Nonfat (n =303)	Coconut (n =61)	Almond (n =44)	Cashew (n =30)	Oat (n =15)
Gums	Guar gum	0	5	0	1	4	1
	Locust bean gum	41	22	26	23	26	4
	Xanthan gum	0	29	3	14	0	0
	Pectin	87	139	37	21	17	7
	Agar	0	53	4	17	3	5
	Carrageenan	1	66	0	0	0	0
Starches	Tapioca/Cassava	10	1	9	19	26	3
	Corn	29	150	4	5	7	4
	Potato	0	0	3	0	0	2
	Rice	0	0	20	0	5	0

TABLE 3 Vitamins and minerals present in the ingredient statement for dairy and plant-based yogurts.

Function	Ingredient	Dairy n=462		Plant-Based n=150			
		Full-Fat (n =159)	Low& Nonfat (n =303)	Coconut (n =61)	Almond (n =44)	Cashew (n =30)	Oat (n =15)
Vitamins & Minerals[a]	Calcium citrate	0	4	16	11	0	4
	Calcium/Tricalcium phosphate	1	32	14	8	0	1
	Calcium carbonate	0	0	0	0	0	1
	"Milk calcium"	10	22	0	0	0	0
	Calcium lactate	0	37	0	0	0	0
	Dipotassium phosphate	0	0	9	0	0	0
	Vitamin B12	0	0	25	0	0	4
	Vitamin D	14	8	0	0	0	0
	Vitamin D3	23	211	0	0	0	0
	Vitamin D2	0	0	25	8	0	4
	Vitamin E	0	4	3	0	0	0

[a]No ingredient lists contained vitamin B2 or vitamin C.

provide all essential amino acids. However, no products in this study met this definition of a hybrid product. Moreover, there are additional benefits of developing hybrid products, including the positive impact of providing a desirable sensory appeal. Hybrid products may reduce the barriers for reluctant consumers to adopt a more sustainable diet. Indeed, a recent study reported that a blended dairy yogurt with a 25% replacement of plant-based yogurt reported no difference in liking compared to 100% dairy yogurt (37). This suggests partial replacement can help consumers shift to more sustainable options. Another opportunity to improve the protein content is a combination or blend of two or more different plant-based proteins. Four products in this study's database contained a combination of two plant-protein bases: coconut and cashew. While not included in statistical analysis, these products contained an average protein value of 1.8 g per 100 g, which was less than all other plant-based yogurts except for coconut yogurt (1.2 g per 100 g). There are also additional strategies that could be explored for improving the protein content of plant-based yogurts, such as the utilization of pulses (21) or legumes (16).

It is evident that the previous seven studies, all published from 2020 onward, represent a growing scientific interest in the nutritional properties of plant-based yogurts. Bases included in these studies were coconut (15, 16, 19–21), almond (16, 20, 21), cashew (16, 20, 21), oat (16, 21), soy (15, 16, 20, 21), hemp (20, 21), pea (16, 21), lupin (21), and flaxseed (21). Some studies also combined bases into one category (15, 19) or categorized blends of bases (16). This diversity of bases demonstrates that a blanket statement regarding plant-based yogurts' nutrition cannot be made. The present study underscores the importance of segmenting plant-based yogurts according to their primary ingredient. Additionally, as consumers continue to adopt a plant-based diet, it is important that these distinctions are made to recognize that not all plant-based yogurts are nutritionally equal.

4.2. Micronutrients and fortification of plant-based yogurts

Consumers may adopt a plant-based diet for various reasons, but perceived healthfulness has been identified as an important driver (13, 38). In addition to considering macronutrient content and energy density, it is important to compare the micronutrient content of plant-based yogurt. For example, consumers may consider dairy yogurt to be a source of some vitamins and minerals, such as calcium and vitamin B12. Results from our study differ from previous reports for some nutrients, which may be a result of the base categories. In studies that combined all plant-based yogurt bases into one category and compared to dairy yogurts (17–19), sodium content was not significantly different. In agreement with Clegg and colleagues (15), our results found significant differences in the sodium content between dairy and the different plant-based yogurt bases. However, our results indicate that both full-fat and low and nonfat dairy yogurts contain significantly higher sodium levels than plant-based yogurts. This finding contradicts findings by Clegg and colleagues (15) which reported plant-based yogurts to contain significantly more sodium than dairy yogurts.

As described above, preliminary data suggests that a diet that reduces or removes dairy may create a risk of inadequate consumption of micronutrients such as calcium, vitamin D, potassium, and vitamin B12 (25, 39). Thus, it has been recommended that plant-based dairy substitutes be fortified with micronutrients to compensate for this deficiency (25). In this section, we discuss the vitamin and mineral content alongside the number of products that enhanced their content with fortification.

Calcium levels in plant-based yogurts were significantly lower than in dairy yogurts. In our database, 36.7% of plant-based yogurts' formulations contained a calcium salt. This suggests some of the products would provide equivalent amounts of calcium, yet on average all plant-based yogurts did not provide equivalent amounts of calcium. As cow's milk is considered a food rich in calcium (14), fortification of plant-based yogurts is an opportunity for calcium content improvement. In contrast with Clegg and colleagues (15), vitamin D was significantly different amongst the yogurt bases. In this study, 24.7% of plant-based and 56.3% of dairy yogurts contained some form of vitamin D as an additive. Vitamin D fortification, like calcium, is an opportunity for plant-based yogurts to improve from a nutritional standpoint.

In the U.S., potassium is a micronutrient required to be listed on the Nutrition Facts Label (30). However, here we present the first study, both in the U.S. and internationally, to analyze and compare potassium levels in plant-based and dairy yogurts. Non-traditional diets with novel plant-based substitutes did not meet daily potassium requirements (39), so consumers who rely on plant-based yogurts to fulfill this need may find their diets lacking. Full-fat dairy yogurts and low and nonfat dairy yogurts contained an average of 171.9 mg and 157.0 mg of potassium per 100 g, respectively. Future plant-based yogurt nutritional studies should thus include potassium. This is especially important because all plant-based yogurts had lower levels of potassium than dairy yogurts. Fortification of potassium is an opportunity to increase the potassium levels in plant-based yogurts, especially since only 9 plant-based yogurts (all coconut) were fortified with dipotassium phosphate.

Animal-based foods provide sufficient amounts of vitamin B12, whereas fortification is required to incorporate vitamin B12 to plant-based foods. Dairy yogurt is considered a good source of vitamin B12 (e.g., 0.61 mcg of vitamin B12 per 100 g of nonfat yogurt) (14). However, only 29 (19.3%) of this study's 150 plant-based yogurts were formulated with vitamin B12. Based on our micronutrient analysis, the coconut yogurts that contained vitamin B12 were found to have a significantly higher content compared to low and nonfat yogurts. Craig and Brothers (16) reported that 21.7% of the studied plant-based yogurts had vitamin B12 fortification levels that reached at least 10% DV (DV is 2.4 mcg (40)). These yogurts included coconut, coconut with another ingredient, oat, and a legume-blend. Clegg and colleagues (15) also reported on vitamin B12 content in coconut (0.38 mcg per 100 g) and soy (0.37 mcg per 100 g) yogurts. Consumers reducing dairy products from their diet may need to supplement with vitamin B12 or select plant-based dairy alternatives that include the fortification of vitamin B12. This difference highlights the importance and opportunity to improve the nutritional profile of these yogurts. While this study did not correlate the frequency of additive vitamins and minerals to micronutrient levels, further research can establish the effects of additives on micronutrient properties. Additionally, the bioavailability of plant-based ingredients is variable and is generally lower than animal-based ingredients (28). More work is needed to understand the bioavailability of these ingredients in these food matrices.

4.3. Application of the NRF index to dairy and plant-based yogurts

The NRF Index has previously been used to identify dairy yogurt as a highly nutrient-dense food in comparison to popular American snacks (33). However, the NRF Index has not yet been applied to plant-based yogurts. The NRF Index provides an integrative assessment of the nutrient density, expanding on the individual nutrient analysis. It is important to note the high standard deviations observed in the present study for all the NRF6.3 scores for each yogurt base, indicating high variability in the nutrient density for both dairy and plant-based yogurt bases. The NRF6.3 Index was based on a positive sub-score for protein, fiber, calcium, iron, potassium, and vitamin D; and a negative sub-score for total sugar, sodium, and saturated fat. A higher NRF score indicates a higher nutrient density. In our study, almond and oat yogurts scored higher than full-fat and low and nonfat dairy yogurts. Therefore, almond and oat yogurts are more nutritionally dense than dairy yogurts. Based on our macronutrient and micronutrient analysis, almond and oat yogurts' higher NRF scores can be attributed to their low levels of total sugar, sodium, and saturated fat. All three of these macronutrient levels were lower in almond and oat yogurts than dairy yogurts. Regarding sodium and total sugar content, almond and oat yogurts contained significantly lower levels than dairy yogurts. Though cashew yogurts had a lower NRF score than both dairy categories, the scores were not significantly different. This indicates that cashew yogurt has a similar nutrient density to dairy yogurts. Coconut yogurt had the lowest nutrient density, likely due to its high saturated fat content and low protein levels. As almond and oat yogurts are already more nutrient dense than dairy yogurts, further product development can address any sensorial disparities compared to dairy yogurts. Coconut yogurts may need reformulation to first address their distinct nutritional profiles compared to dairy yogurts.

A previous study has used a different nutrient profiling method for plant-based yogurts (19), and a different study used the NRF Index for plant-based milk alternatives (23). Katidi and colleagues (19) utilized the Nutri-Score algorithm to assess the nutrient quality of plant-based yogurts available in Greece. They reported that most plant-based yogurts were given a higher Nutri-Score than their dairy equivalents. Drewnowski (34) utilized the NRF Index to examine the nutrient density of plant-based milk alternatives (23), which is most comparable to this study's NRF results. Drewnowski's model (NRF5.3) contained the same limiting nutrients as the present study; however, for qualifying nutrients, it included vitamin A and vitamin B12, which were not used in the present study. In our study and Drewnowski's study, the order of the NRF scores from highest to lowest was the same: almond, oat, cashew, and coconut.

While this study's NRF model provides a consistent way to compare the overall nutrient profile, which considers nutrients that should be included and limited in a food product, there are some limitations of this approach in the present study. Prior to the calculation of the NRF6.3 score, 45% of the products in the database were removed due to missing one or more macronutrients and/or micronutrients selected for the model. This was largely due to missing vitamin D and potassium values, as the FDA did not require reporting these micronutrients prior to 2020. Despite this limitation, the present analysis is the first to use the NRF Index for dairy and plant-based yogurts. The NRF Index provides an advantage when comparing the nutritional compositions of products. Rather than comparing individual nutrients of a product to another product, the NRF Index examines the overall nutrient density of a product (9).

Overall, using the NRF Index to analyze the nutritional profiles of yogurts provides valuable insight into the nutrient density of commercially available plant-based yogurts. The NRF6.3 scores provide a holistic view of the nutritional quality of the plant-based products in comparison to conventional yogurt products. This study highlights that some product categories may provide advantages regarding the overall nutrient quality, yet the industry needs to continue to consider individual macronutrients and micronutrients to improve the overall nutrient composition.

4.4. Additive ingredients in plant-based yogurts

Sensorial properties have been identified as barriers to plant-based dairy consumption (26). Raw plant materials are known to evoke bitter, beany, astringent, herbaceous tastes, and odors, which can be unappealing to dairy yogurt consumers (36). Specific to plant-based yogurts, the texture was found to have a major effect on product liking (41). For example, mouthfeel at the beginning of mastication was found to have an important effect on the liking of oat yogurts (42). The poor textural profile of plant-based yogurts has been attributed to the lack of globular plant proteins' ability to mimic/recreate the molecular attributes of casein (26). The food industry and researchers have noted significant challenges in recreating the textural and mouthfeel characteristics of plant-based products (36, 43). Therefore, the addition of thickeners and structural agents (i.e., gums and starches) contributes to the viscosity of plant-based gels (44) and may create a more sensorially acceptable plant-based yogurt product.

Here, we examined the incorporation of thickening agents in both dairy and plant-based yogurts. Gums can be used in plant-based yogurts to prevent syneresis (45) and can be utilized as thickening agents (46). In our study, many plant-based yogurts used gums in their formulations; pectin and locust bean gum were the most popular. Similar to Boeck and colleagues (21) and Craig and Brothers (16), the most used gums in the plant-based yogurts were pectin (54.7%), locust bean gum (52.7%), and agar (19.3%) Like gums, starches can be used in plant-based products for gelling, binding, and stabilizing purposes (47). Similar to Boeck et al. (21), the most commonly used starch was tapioca (38.0%).

Gums and starches are included in plant-based yogurts to increase consumer acceptance by improving the sensory and mouthfeel characteristics (25, 48). However, the use of these ingredients may conflict with the recent and growing consumer trend of a "clean label" defined by a simple ingredient list and minimal processing (13, 26, 27). Overall, almond yogurt contained the second-highest total number of gums and starches in all yogurts, but the highest NRF6.3 score. Almond yogurts are the most popular plant-based yogurt purchased in the U.S. (9), suggesting that consumers may be willing to accept additive ingredients if the product is nutrient dense. Further research is needed to measure how willing consumers are to accept plant-based yogurts with a high nutrient composition but also a high additive count.

5. Conclusion

As consumers adopt plant-based diets for health reasons, it is important to examine the extent to which plant-based yogurt alternatives match the nutritional profile of dairy yogurts. Our analysis, based on data from Mintel GNPD for commercial products in the U.S., demonstrated that while plant-based yogurts contain less total sugar, less sodium, and more fiber than dairy yogurts, they contain less protein, calcium, and potassium than dairy yogurts. A nutrient assessment revealed that when considering key nutrients provided by dairy yogurts, oat yogurts were the most similar to low and nonfat dairy yogurts. Further, when considering the nutrient density and the energy density of commercial yogurts, oat and almond appeared to be similar or better compared to dairy yogurts, while cashew yogurts were similar to low and nonfat dairy yogurts. Coconut had the lowest nutrient density and highest energy density. Fortification with vitamins and minerals has the potential to improve the nutritional profile (e.g., calcium and vitamin B12). With the current strategy for plant-based products to be substituted for conventional dairy products, there is a need to consider the desirable nutritional benefits of dairy yogurt, such as protein, vitamin B12, and calcium, and the minimization of nutrients such as total sugar, sodium, and saturated fat.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AD'A, AK, and AN contributed to the conception and design of the study, interpretation of the results, and wrote and/or contributed to all sections of the manuscript. AD'A organized the database, performed the statistical analysis, and wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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Supplementary material

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Perception of cultured "meat" by Italian, Portuguese and Spanish consumers

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The aim of this study was to investigate how consumers (n = 2,171) originated from South-Western Europe (Italy, Portugal, and Spain) perceive cultured "meat" (CM) and if their demographic characteristics (origin, gender, age, education, occupation, and meat consumption) are related to their willingness to try (WTT), to regularly eat (WTE) and to pay (WTP) for CM. We found the current respondents had an initially positive attitude towards CM: 49% of them perceived CM as "promising and/or acceptable" and 23% "fun and/or intriguing" whereas 29% considered it as "absurd and/or disgusting". In addition, 66 and 25% would be willing and not willing to try CM, respectively. However, 43% had no WTE for CM and, 94% would not pay more for CM compared to conventional meat. Age and especially occupation were good indicators of consumer acceptance of CM. Respondents of 18–30 years of age had the highest acceptance. Respondents outside the meat sector had the highest WTE and people working within the meat sector had the lowest WTE, scientists (within or outside the meat sector) had the highest WTT, people not scientists but within the meat sector had the lowest WTT. Additionally, we found that men are more likely to accept CM than women, Spanish-speaking consumers had the highest WTT and WTE, people with vegan and vegetarian diets may pay more for CM but generally no more than for conventional meat. The perceptions that CM may be more eco-friendly, ethical, safe and healthy than conventional meat, and to a lower extent, the perception that current meat production causes ethical and environmental problems are likely to be major motives for the current respondents to try, regularly eat and pay for CM. On the opposite, lower perceptions of CM benefits and of conventional meat weaknesses more generally, plus emotional resistance towards CM are main barriers to accept CM.

KEYWORDS

survey, consumer, cultured "meat", acceptance, barriers, motives

Introduction

In recent years, the animal production industry has been challenged by the need to meet the growing global demand for meat while also reducing the negative impacts of livestock and meat production. These negative effects are highlighted in the press media (such as greenhouse gas emissions (GHG), feed-food competition, low animal welfare, and potential risks for human heath). Although meat consumption may be slowing down in developed countries, it is projected that global meat consumption will continue to grow as populations and incomes increase especially in some developing countries (1). As it is expected, global meat consumption would increase by 1.4% per year (2). Approximately 31% of global human-caused GHG emissions come from agri-food production, where meat accounts for a significant proportion (3). It is estimated that more than 70 billion farm animals are raised and slaughtered for meat production per year (4). A proportion of them is raised in intensive farming conditions and slaughtered at a very young age. Additionally, animal food consumption raises a set of health issues such as the risk of colorectal cancer (5, 6).

Dietary changes can bring ethical and environmental benefits to a large extent, which is not achieved yet by our food system (7). For most humans (except vegetarians), eating meat is perceived as natural, normal and necessary (8) with unique sensory and flavor properties. Meat consumption is reinforced by ingrained dietary habits, social norms, values and policy actions (7). Moreover, vegetarianism is a personal choice, meat-free diet may not be acceptable for everyone and may not be a solution anyway.

While some authors are promoting agroecology to change our current production systems to improve their sustainability (9, 10), the development of meat alternatives has been promoted as a good solution. Market share of meat substitutes grows as consumer acceptance increases due to potential ethical, safety and so-called environmental benefits. In fact, for example, plant-based meat alternatives generally may have less GHG than conventional meat (11). However, it depends on the production process, it was reported that in one scenario, plant-based meat production had higher carbon footprint than conventional beef produced on well-managed pastures (12).

Cultured "meat" (CM) is also presented to have a potential to drastically reduce environmental externalities according to some authors (13) but not all (14). As an innovation breakthrough in food production, the basic technique of CM is tissue engineering. Satellite muscle cells and fibro-adipogenic cells are cultured in culture medium allowing their proliferation and differentiation to produce muscle fibers and fat tissues which are presented as meat when mixed together (15). Even if the production of animal-free medium seems still uncertain in terms of large scale production and cost (16), and even the biopsy procedure can still cause animal pain to some extent, the introduction of CM is likely to reduce the number of slaughtered animals. Although the process of culturing cells is hardly ever perfectly controlled and even if some unexpected safety issues may arise (17), food-borne pathogens is likely to be reduced compared to animal farming and production. As for the potential environmental benefits CM can bring, it has so far not been precisely assessed but relies more on forecasts. It will take a long time to confirm these conclusions, which makes them highly speculated (18). As it was demonstrated by Escobar et al. (14), the calculation of the beneficial contribution of CM to the environment depends on how much reliable data is available.

Compared to other meat alternatives, CM might be the closest one to meat in terms of molecular and organoleptic properties even its composition is not known yet (19). Despite so, CM is less favored than plant- and even insect-based meat substitutes (20–22). Moreover, this may incite vegetarians who like meat but do not eat meat for animal and environment protection to eat meat again. Although it was found that vegetarians would be more likely to perceive the potential benefits of CM, they were still less interested in trying it (23).

At present, CM is not yet commercially available, except for the first commercial product (chicken bites/chicken nuggets from the American startup Eat Just) distributed in 1,880 restaurants of the same chain in Singapore after receiving approval from the Singapore Food Authority (24). Thus, the commercial availability of the first cultured meat (CM) product lays the foundation and paves the way for other such meat alternatives to enter the worldwide food market (25). Without actually being exposed to the product, the study of consumer acceptance of CM is based on hypothesis and assumptions. To date, most of the literature has examined consumer acceptance through survey studies. Although more and more studies have been conducted with representative samples, what the population would be willing to do is not precisely known since consumers' answers vary according to origin and cultural factors. However, from a practical point of view, hypothetical studies on the acceptance and/or willingness of a representative population for a product that is not yet available (such as CM) may be inherently less reliable. Herein, the study of consumer acceptance would be more relevant if we could find some indicators (i.e., motives, barriers) that would be good predictors of consumer acceptance.

The main factors that are affecting consumer perception and acceptance of CM are ethical, environmental concerns and issues related to the production process, in interaction with doubts, neophobia, fear and disgust (26). The perception of those factors varies between consumers in different sociodemographic segments. This study therefore seeks to obtain data which would enrich consumer acceptance research on CM. There are two primary aims of this study: (1) to capture perception of CM in specific consumer segments from citizens with origin from South-Western Europe, and (2) to investigate potential indicators (motives, barriers) of consumer acceptance of CM. Results will be analyzed considering published data with respondents from other countries (China, Brazil, France) using the same survey (27–29). Furthermore, compared to our previous studies, novel statistical approaches were developed to better identify barriers and motives of acceptance of CM.

Materials and methods

Questionnaire design

As mentioned above, this study is an extension in other countries of previous published research with the same questionnaire (27–29) and with additional statistical approaches. Only some of the questions below and data were used in order to obtain key information that met the purpose of this study. The complete questionnaire can be seen in Hocquette et al. (29). The questions used in this study are presented in Table 1.

Data collection

The survey was distributed in Italy, Spain and Portugal through social networks and on campus questionnaire dissemination. Although, we note that a small part of the data was collected from people who live in other countries but speak Italian, Spanish and Portuguese, these data was still worthwhile to be used since either people originated from these three countries or those who speak these three languages as their first language are considered to have the corresponding cultural, local and dietary backgrounds. In the end, 2,171 answers including 46.7% Italian data, 31% Portuguese data and 22.3% Spanish data were collected, and the demographic information is detailed in Tables 1, 2.

Statistical analysis

The data was analyzed using R software (version. 4.1.1) and IBM SPSS 25 depending on the different output needs such as plotting.

The demographic variables and their categories are presented in Tables 1, 2. Some treatments of categories need to be specified such as for age, 18–30 years of age was considered as young, 31–50 years of age was considered as middle-aged and more than 51 years of age was considered as senior or old in this study. For meat consumption, people never eat meat were considered as vegans and/or vegetarians. These treatments were used in the following analysis with General Linear Model (GLM) and logistic regression modeling. Three types of statistical analyses were performed with this transformed data set.

First, variance analysis (ANOVA) was performed with the GLM procedure in SPSS as previously described (27, 29) to examine the difference in WTT, WTE, and WTP depending on respondent groups based on different demographic characteristics. As in previous studies (27), some, but not all of the assumptions of ANOVA were sometimes violated in this survey case, such as normality of distributions and homogeneity of variances. Therefore, we ran a Welch's ANOVA, which does not require the homogeneity of variance assumption, and we obtained extremely similar results compared to ANOVA which is considered as being robust (30). Based on these observations, we proceeded with ANOVA since the Welch's ANOVA does not accept interactions. *Post-hoc* test was performed using Bonferroni test with the Bonferroni correction for pairwise comparisons between groups with significant difference, which was determined at the level of $p < 0.05$.

Second, to identify the potential motives and barriers to the acceptance of CM, Pearson correlation analysis was thereafter performed by R software to determine the relationships between variables (WTT, WTE, WTP, and other questions regarding the perception of conventional meat production and of CM). To have an overall perception of conventional meat production and CM, respectively, two overall variables "Overall perception of conventional meat production" and "Overall perception of CM" were created. Overall perception of conventional meat production was calculated by merging answers to two questions: (1) Does meat production cause ethical problems? and (2) Does meat production cause environmental problems? as follow 0.5 × answer to question 1 + 0.5 × answer to question 2 (both from a scale from 1 to 5). Overall perception of CM was calculated by merging answers to four questions: (1) How ethical do you think CM would be compared to conventional meat? (2) How eco-friendly do you think CM would be compared to conventional meat? (3) How healthy, safe and nutritional do you think CM would be compared to conventional meat? and (4) How tasty do you think CM would be compared to conventional meat? as follow 0.25 × answer to question 1 + 0.25 × answer to question 2 + 0.25 × answer to question 3 + 0.25 × answer to question 4.

Third, logistic regression was developed to identify barriers and motives to accept CM. As demonstrated by Verbeke et al. (31), since this novel product is not yet commercially available on a large scale and to be consumed frequently, it is difficult to obtain real data regarding consumer WTT and WTE. Nevertheless, consumer willingness is highly driven by the perception of the product, and emotional resistance to the concept of CM can negatively affect consumers' perception of this product and their willingness to try and eat (27, 29). Combined with relevant demographic variables, this analysis considered also the variability in emotional resistance, allowing to investigate the potential profile of CM adopters and rejectors. This modeling approach was greatly inspired by the research of Verbeke et al. (31).

Willingness to try for CM was analyzed as a discrete choice (yes-1, no-0) by combining the response categories "definitely yes" and "probably yes" as "yes" (65.5%), and "definitely no" and "probably no" as "no" for WTT (24.7%), "Unsure" was not used in this analysis; "I would be willing to regularly eat CM at restaurant/home/in ready-to-eat meals" as "yes" (56.7%) and "I do not want to regularly eat CM" as "no" (43.3%).

Binary logistic regression was used to model the discrete choice in terms of WTT and WTE. If the latent variable z_i is greater than zero, the binary response y_i (for WTT or WTE) for respondent i takes a value of one; otherwise, y_i takes a value of zero:

$$\begin{cases} y_i = 1 \; if \; z_i > 0 \\ y_i = 0 \; if \; z_i \leq 0 \end{cases}$$

The latent variable z_i is constructed with a regression model where x_{ki} represents explanatory variables that from 1 to k explaining WTT and WTE for participant i with β_k as the coefficient that indicates the effect of x_{ki} on z_i, and where ε_i represents the random error for respondent i, as below:

$$z_i = \beta_0 + \sum_{k=1}^{k} (\beta_k x_{ki}) + \varepsilon_i$$

In this study, z_i is specified by a set of explanatory variables as $z_i = \beta 0 + \beta 1\text{Gender[Female]}_i + \beta 2\text{Age[} > 50 \text{ years of age]}_i + \beta 3\text{Origin[Italy]}_i + \beta 4\textit{Occupation}\text{[not scientists working within the meat sector]}_i + \beta 5\text{Meat consumption [Never]}_i + \beta 6\text{Income[high income]}_i + \beta 7\text{Education[high level]}_i + \beta 8\text{Familiarity[never heard]}_i + \varepsilon\, i$.

In the current model, females, more than 50 years of age, originated from Italy, not scientist, working in the meat sector, who never consume meat (considered as vegans/vegetarians), with a high income, a high education level and who never heard about

TABLE 1 Questions of the CM questionnaire used in this study.

Section	Question	Answer/Scale
Demographic information	Gender	Female; Male; No answer
	Age	18–30 years of age; 31–50 years of age; >50 years of age
	Origin	Italian - people originated from Italy and/or mainly Italian-speaking; Portuguese - people originated from Portugal and/or mainly Portuguese-speaking; Spanish - people originated from Spain and/or mainly Spanish-speaking, even if few respondents live in South America.
	Education	Lower education - prior to university; Medium education - studying at university or having obtained a bachelor's degree; Higher education - having obtained a master's degree (or studying to do so) and above.
	Income (monthly net income)	0–1,500 €; 1,500–2,000 €; 2,000–2,500 €; 2,500–3,000 €; 3,000–4,000 €; >4,000 €; No answer Income level was sorted as: Low income – <2,000 €; Medium income – 2,000—3,000 €; High income –>3,000 €
	Occupation	Not scientists, work outside the meat sector; Not scientists, work within the meat sector; Scientists, work outside the meat sector; Scientists, work within the meat sector.
	Meat consumption	Never: vegetarian or vegan diet; Rarely: weekly or less; Regularly: several times a week; Daily or at every meal
	Familiarity with CM	Yes, I have heard of CM; No, I never heard of CM
Societal challenges that faced by conventional meat production	Do you think the conventional meat industry cause ethical problems?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
	Do you think the conventional meat industry cause environmental problems?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
	Do you think reducing meat consumption could be a good solution to resolve above problems?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
Potential challenges that faced by CM	How ethical do you think CM would be compared to conventional meat?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
	How eco-friendly do you think CM would be compared to conventional meat?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
	How healthy, safe and nutritious do you think CM would be compared to conventional meat?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more

(Continued)

TABLE 1 (Continued)

Section	Question	Answer/Scale
	How tasty do you think CM would be compared to conventional meat?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more
Acceptance of CM	Would you be willing to try CM?	(1)-Definitely no; (2)-Probably no; (3)-Unsure; (4)-Probably yes; (5)-Definitely yes
	Would you be willing to eat regularly CM?	0-No (I do not want to eat CM regularly); 1-Yes (I want to eat CM at restaurant/home/in ready-to-eat meals)
	How much would you be willing to pay for CM compared to conventional meat?	(1)-Much less than conventional meat; (2)-Less than conventional meat; (3)-Same as conventional meat; (4)-More than conventional meat; (5)-Much more than conventional meat
Perception of CM	What do you think of CM?	It is promising and/or acceptable; It is fun and/or intriguing; It is absurd and/or disgusting
	Do you have emotional resistance to accept CM?	(1)-Much less; (2)-Less; (3)-Unsure; (4)-More; (5)-Much more

CM served as the reference category for demographic variables of gender, age, origin, occupation, meat consumption, income, education and familiarity with CM.

The logistic function used to transform y_i from z_i is based on the relationship between the probability p_i of dependent variable y_i (WTT or WTE) and the explanatory variable x_k (gender, age, etc.) as below:

$$p_i = prob(y_i = 1) = \frac{e^{z_i}}{1 + e^{z_i}} = \frac{e^{\beta_0} + \sum_{k=1}^{k} \beta_k x_{ki}}{1 + e^{\beta_0} + \sum_{k=1}^{k} \beta_k x_{ki}}$$

Meanwhile:

$$log(\frac{p_i}{1 - p_i}) = z_i = \beta_0 + \sum_{k=1}^{k} (\beta_k x_{ki}) + \varepsilon_i$$

regression coefficient (β) was estimated based on maximum likelihood estimation and is presented with odds ratio [EXP (β), OR] and significance level (p-value).

Results

Characteristics and overall answers of the respondents

Basic demographic information of the current respondents

Of the total respondents, 56.7% were females and 42.5% were males (and 0.8% were unwilling to answer this question), of whom 46.7% were originated from Italy and/or mainly Italian-speaking, 31% were originated from Portugal and/or mainly Portuguese-speaking and 22.3% were originated from Spain and/or mainly Spanish-speaking. The current sample was mainly middle-aged and young people (39.5 and 37.2%, respectively), more than half (53.8%) had a net monthly income of less than 2,000 €. Most of them were well-educated (98.1% pursuing and/or have obtained a degree of bachelor, master or Ph.D.), working outside the meat sector (72.8%), being meat eaters (90.1%) with various frequencies (from rarely to daily), and being familiar with CM or at least have heard about this novel food biotechnology (Table 2).

Overall perception and willingness

Considering together all answers from the current respondents, the overall perception of conventional meat production and CM were observed as well as their WTT, WTE, and WTP CM (Table 3). In general, more than half of the current respondents believe that conventional meat production does cause a considerable amount of ethical and environmental problems (54.3, 62.6%) and reducing meat consumption could be a good solution to resolve those problems for 50.7% of the respondents. In general, they do believe CM would be more ethical and eco-friendly than conventional meat, but do not seem to be too much convinced that CM could be safer and tastier than conventional meat. This novel biotechnology does not provoke much emotional resistance (only of 32.8% of the current participants). In addition, 48.8% of them considered CM as "promising and/or acceptable," 22.7% perceived CM as "fun and/or intriguing" and 28.5% felt CM as "absurd and/or disgusting." Overall, the current respondents would be willing to try and regularly eat CM, but would be only willing to pay a lower price than conventional meat. A total of 65.5% of the respondents would be willing to try CM (26.7% answered "Definitely yes" and 38.8% "Probably yes"), 34.5% respondents were unwilling to try or were unsure about CM (10.5% answered "Definitely no," 14.2% "Probably no" and 9.8% "Unsure"). A total of 56.7% of respondents

TABLE 2 Demographic information of the current respondents (n = 2,171).

Demographic	Category	Number	Percentage
Gender	Female	1,232	56.7
	Male	923	42.5
Age	18–30 years of age	807	37.2
	31–50 years of age	857	39.5
	>50 years of age	507	23.4
Origin	Italy	1,014	46.7
	Portugal	673	31.0
	Spain	484	22.3
Education	Low level	42	1.9
	Medium level	1,144	52.7
	High level	960	44.2
Occupation	Not scientists and outside the meat sector	1,025	47.2
	Not scientists and within the meat sector	321	14.8
	Scientists outside the meat sector	555	25.6
	Scientists within the meat sector	270	12.4
Monthly net income	0–1,500 €	782	36.0
	1,500–2,000 €	386	17.8
	2,000–2,500 €	219	10.1
	2,500–3,000 €	98	4.5
	3,000–4,000 €	76	3.5
	>4,000 €	89	4.1
	No answer	521	24.0
Income*	Low income	1,168	53.8
	Medium income	317	14.6
	High income	165	7.6
	No answer	521	24.0
Meat consumption	Never: vegetarian or vegan diet	214	9.9
	Rarely: weekly or less	477	22.0
	Regularly: several times a week	1,268	58.4
	Daily or at every meal	212	9.8
Familiarity	Ever heard	1,660	76.5
	Never heard	511	23.5

*Classification of monthly net income into different levels.

would be willing to regularly eat CM (at home, restaurants or in ready-made meals), which means that 43.3% of respondents did not want to regularly eat CM at all. Only 5.7% of respondents would be willing to pay more for CM than conventional meat, 31.5% would be willing to pay the same price for CM as conventional meat, 62.8% would be willing to pay only less or much less or even nothing.

Determinants of WTT, WTE, and WTP for CM

Determinants of WTT

A logistic regression was performed to ascertain the effects of gender, age, origin, occupation, meat consumption, income, education and familiarity on the likelihood that participants would be willing to try and to regularly eat CM. The model correctly classified 72.6% of the current responses of WTT. No significant differences were found for WTT between males and females ($p > 0.05$, Table 4) based on variance analysis in general linear model; nevertheless, the odds ratio of WTT is 1.3 times (OR = 1.29) greater for males as opposed to females ($p < 0.05$, Table 5) in logistic regression model. There was no difference of WTT between mid-aged and old participants ($p > 0.05$, Tables 4, 5). Spanish-speaking participants had the highest WTT ($p < 0.001$, Table 4) with 2 times (OR = 2.18) more likely than Italian-speaking participants, Portuguese-speaking people were 1.7 times (OR = 1.66) more likely to try CM than Italian-speaking participants ($p < 0.001$, Table 5). Low educated participants

TABLE 3 Current perceptions of conventional meat production and cultured "meat" (CM) and willingness to try (WTT), willingness to eat (WTE), willingness to pay (WTP) for cultured "meat" (CM) based on 2,171 responses.

Perception of conventional meat production[1]	Mean	SD
Do you think the conventional meat industry cause ethical problems?	3.55	1.30
Do you think the conventional meat industry cause environmental problems?	3.73	1.28
Do you think reducing meat consumption could be a good solution to resolve above problems?	3.38	1.45
Perception of CM[1]		
How ethical do you think CM would be compared to conventional meat?	3.07	1.42
How eco-friendly do you think CM would be compared to conventional meat?	3.09	1.35
How healthy, safe and nutritional do you think CM would be compared to conventional meat?	2.85	1.24
How tasty do you think CM would be compared to conventional meat?	2.46	1.21
Do you have emotional resistance to try CM?	2.78	1.44
Willingness		
Would you be willing to try CM?[1]	3.57	1.30
Would you be willing to regularly eat CM?[2]	0.57	0.50
How much would you be willing to pay for CM compared to conventional meat?[3]	2.22	0.87

[1]Response rated as (1)-Much less, (2)-Less, (3)-Unsure, (4)-More, (5)-Much more or Response rated as (1)-Definitely no, (2)-Probably no, (3)-Unsure, (4)-Probably yes, (5)-Definitely yes.
[2]Response rated as 0-No, 1-Yes.
[3]Response rated as (1)-Much less than conventional meat, (2)-Less than conventional meat, (3)-Same as conventional meat, (4)-More than conventional meat, (5)-Much more than conventional meat.

had the lowest WTT than medium and high educated people ($p < 0.01$, Table 4). There was no difference for WTT between different income groups ($p > 0.05$, Table 4), also, the predictive effect of income to WTT was not significant in the current logistic regression model ($p > 0.05$, Table 5). Scientists outside the meat sector had the highest WTT ($p < 0.001$, Table 4) and were 4 times (OR = 3.96) more likely to try CM than people who were not scientists but work within the meat sector that had the lowest WTT ($p < 0.001$, Table 5). Participants who were meat scientists were 2.7 times (OR = 2.66) more likely to try CM than participants who were not scientists but work within the meat sector ($p < 0.001$, Table 5). Participants who were not scientist and outside the meat sector were 2.4 times (OR = 2.41) more likely to try and eat CM than people who were not scientists but work within the meat sector ($p < 0.001$, Table 5). There was no difference for WTT among groups with different meat consumption levels ($p > 0.05$, Table 4). Nonetheless, rarely meat eaters were almost two times (OR = 1.80) more likely to try CM than vegans/vegetarians ($p < 0.01$, Table 5).

Determinants of WTE regularly CM

The logistic regression model correctly classified 63.2% of the current responses of WTE. According to ANOVA, no significant differences were found for WTE for CM between males and females ($p > 0.05$, Table 4) but according to logistic regression model, the odds ratio of WTE is 1.3 times (OR = 1.27) greater for males as opposed to females ($p < 0.05$, Table 3). Young people had the highest WTE ($p < 0.001$, Table 4) because they were twice (OR = 2.04) more likely than mid-aged and old people to regularly eat CM, there was no difference of WTE between mid-aged and old participants ($p > 0.05$, Tables 4, 5). Spanish-speaking people had the highest WTE ($p < 0.001$, Table 4) because they were three times (OR = 2.92) more likely than Italian-speaking people to regularly eat CM ($p < 0.001$, Table 5), Portuguese-speaking people were 1.8 times (OR = 1.75) more likely to eat CM than Italian-speaking people ($p < 0.001$, Table 5). Scientists outside the meat sector had the highest WTE ($p < 0.001$, Table 4) and were 3.7 times (OR = 3.69) more likely to eat CM than people who were not scientists but work within the meat sector that had the lowest WTE ($p < 0.001$, Table 4). Participants who were meat scientists were 1.6 times more likely to eat CM than people who were not scientists but work within the meat sector, people who were not scientists and outside the meat sector were 2.7 times (OR = 2.68) more likely to eat CM than people who were not scientists but work within the meat sector ($p < 0.001$, Table 5). Participants with the lowest income had higher WTE than medium income people ($p < 0.05$, Table 4). There was no difference for WTE among groups with different meat consumption levels ($p > 0.05$, Table 4). Participants who had heard about CM had higher WTT (1.2 times higher than people who had never heard about it) but lower WTE ($p < 0.01$, Table 4).

WTP for CM

Since only 5.7% of the current respondents would be willing to pay for CM at a price higher than conventional meat, it is difficult to transform the data with five categories in binary responses and this makes it impossible to apply logistic regression with WTP. Based on variance analysis with general linear model, it can be seen that females, young people and Italian-speaking participants of the current respondent sample were willing to pay more than males, middle-aged and old people, and compared to Spanish- and Portuguese-speaking participants ($p < 0.001$, Table 4). Participants working outside the meat sector would be willing to pay the most and

TABLE 4 Respondents' willingness to try (WTT), willingness to eat (WTE) and willingness to pay (WTP) for cultured "meat" (CM) according to demographic categories.

Demographic	Category	WTT[1]		WTE[2]		WTP[3]	
		Mean	SD	Mean	SD	Mean	SD
Gender	Female	3.53	1.27	0.56	0.50	2.32[a]	0.85
	Male	3.63	1.33	0.58	0.49	2.09[b]	0.88
Age	18–30 years of age	3.80[a]	1.24	0.65[a]	0.48	2.40[a]	0.87
	31–50 years of age	3.47[b]	1.31	0.54[b]	0.50	2.16[b]	0.85
	> 50 years of age	3.39[b]	1.33	0.49[b]	0.50	2.05[b]	0.85
Origin	Italy	3.55[b]	1.38	0.53[b]	0.50	2.32[a]	0.92
	Portugal	3.47[b]	1.22	0.54[b]	0.50	2.09[b]	0.84
	Spain	3.75[a]	1.22	0.68[a]	0.57	2.19[b]	0.87
Education	Low level	3.05[b]	1.23	0.40	0.50	1.98	0.75
	Medium level	3.53[a]	1.34	0.57	0.50	2.24	0.90
	High level	3.65[a]	1.25	0.57	0.50	2.21	0.83
Occupation	Not scientists outside MS[4]	3.53[b]	1.28	0.61[a]	0.49	2.30[a]	0.86
	Not scientists within MS	3.08[c]	1.40	0.39[b]	0.49	1.79[c]	0.84
	Scientists outside MS	3.86[a]	1.21	0.65[a]	0.48	2.39[a]	0.84
	Scientists within MS	3.70[ab]	1.28	0.46[b]	0.50	2.09[b]	0.82
Income	Low income	3.59	1.29	0.58[a]	0.49	2.22[ab]	0.84
	Medium income	3.58	1.32	0.49[b]	0.50	2.13[b]	0.88
	High income	3.59	1.41	0.53[ab]	0.50	2.12[ab]	0.95
	No answer	3.52	1.27	0.59[a]	0.49	2.30[a]	0.90
Meat consumption	Never	3.46	1.46	0.56	0.50	2.94[a]	0.85
	Rarely	3.69	1.26	0.60	0.49	2.31[b]	0.84
	Regularly	3.55	1.28	0.56	0.50	2.09[c]	0.80
	Daily	3.52	1.36	0.56	0.50	2.08[c]	0.98
Familiarity	Ever heard	3.61a	1.33	0.55[b]	0.48	2.17	0.79
	Never heard	3.44b	1.21	0.62[a]	0.50	2.23	0.89

[1]Response rated as (1)-Definitely no, (2)-Probably no, (3)-Unsure, (4)-Probably yes, (5)-Definitely yes.
[2]Response rated as 0-No, 1-Yes.
[3]Response rated as (1)-Much less than conventional meat, (2)-Less than conventional meat, (3)-Same as conventional meat, (4)-More than conventional meat, (5)-Much more than conventional meat.
[4]MS, meat sector.
Within each demographic category, mean values with different superscript letters significantly differ from each other at the level of $p < 0.05$.

participants working within the meat sector especially those who were not scientists would pay the least for CM ($p < 0.001$, Table 4).

Motives and barriers of CM acceptance

Relationships between participants' acceptance and perception of conventional meat production and of CM

Figure 1 illustrates the correlations between participants' willingness to try, to regularly eat and to pay for CM and their overall perception of conventional meat and of CM.

The perception of ethical and environmental problems caused by conventional meat production has positive correlations with the wish of consumers to reduce their meat consumption (r = 0.60, 0.64, $p < 0.001$). Considering that reducing meat consumption is a good solution is positively correlated with WTT, WTE, and WTP for CM (r = 0.29, 0.31, 0.38, $p < 0.001$). On the opposite, emotional resistance about CM is negatively correlated with the perception that CM may be ethical, eco-friendly, tasty and safe (r = -0.32, -0.30, -0.25, -0.31, $p < 0.001$). Emotional resistance is also negatively correlated with WTT, WTE, and WTP (r = -0.57, -0.42, -0.29, $p < 0.001$).

The overall negative perception of conventional meat production is positively correlated with WTT, WTE, and WTP ($r = 0.30$–0.39, $p < 0.001$). Similarly, the overall positive perception of CM (perceived as ethical, eco-friendly, tasty, and safe) is positively correlated with WTT, WTE, and WTP ($r = 0.50$–0.52, $p < 0.001$).

TABLE 5 Binary logistic regression explaining odds ratio (OR) of respondents' willingness to try (WTT) and willingness to eat (WTE) cultured "meat" (CM) according to sociodemographic characteristics.

Category (ref)		WTT[1]			WTE[2]		
		β[3]	OR[4]	*P*-value	β	OR	*P*-value
Gender (Female)	Male	0.25	1.29	<0.05	0.34	1.27	<0.05
Age (>50 years of age)	18–30 years of age	0.81	2.24	<0.001	0.71	2.04	<0.001
	31–50 years of age	0.23	1.26	0.093	0.16	1.17	0.196
Origin (Italy)	Spain	0.78	2.18	<0.001	1.07	2.92	<0.001
	Portugal	0.51	1.66	<0.001	0.56	1.75	<0.001
Occupation (Not scientists working within MS)	Scientist working within MS[5]	0.97	2.66	<0.001	0.47	1.60	<0.01
	Scientist working outside MS	1.38	3.96	<0.001	1.31	3.69	<0.001
	Not scientist working outside MS	0.88	2.41	<0.001	0.99	2.68	<0.001
Meat consumption (Never)	Daily	0.20	1.22	0.427	−0.05	0.96	0.838
	Regularly	0.30	1.35	0.117	−0.01	0.99	0.997
	Rarely	0.59	1.80	<0.01	0.35	1.41	0.053
Income (High income)	Low income	−0.09	0.91	0.661	0.05	1.05	0.798
	Medium income	0.007	1.01	0.997	−0.15	0.86	0.460
Education (High level)	Low level	−2.81	0.76	0.362	0.19	1.02	0.946
	Medium level	0.11	1.11	0.455	0.33	1.39	0.007
Familiarity (Never heard)	Heard before	0.18	1.20	0.169	−0.17	0.85	0.143

[1]Willingness to try (WTT), the score of WTT was converted into a binary score, the scores of 1 and 2 were converted into 0 (unwilling to try), the score of 4 and 5 were converted into 1 (would be willing to try).
[2]Willingness to eat (WTE), 0–unwilling to regularly eat, 1–would be willing to regularly eat.
[3]β, regression coefficient β is associated with the expected change in log odds of dependent variable (WTT or WTE) per unit change in the explanatory variable.
[4]OR, odds ratio represents the constant effect of an explanatory variable, on the likelihood that dependent variable will change (WTT or WTE).
[5]MS, meat sector.

Predicted probabilities for WTT and WTE CM

Wald Chi-Square (χ^2) value in logistic regression models indicates the predictive power of explanatory variables to the dependent variable. The Wald χ^2 of WTT for gender, age, origin, occupation, meat consumption level, income, education and familiarity are 6.90, 28.66, 20.91, 60.67, 9.66, 1.37, 2.03, and 1.89. The Wald χ^2 of WTE for gender, age, origin, occupation, meat consumption, income, education and familiarity are 8.87, 31.9, 48.9, 82.1, 9.28, 1.94, 7.77, and 2.15. Age, origin and occupation are therefore the most influential factors in both models of WTT and WTE. Considering the effect of origin can be partly skewed due to different sample sizes (46.7, 31.0, and 22.3% of Italian-, Spanish- and Portuguese-speaking participants) and due to nested effects with gender, age and other factors, only the effects of age and occupation are analyzed further in interaction with emotional resistance.

Predicted probabilities for WTT and WTE CM are presented in Figures 2–5 for participants of different age groups and different occupations across the range (1–5) of emotional resistance. Negative effects on WTT and WTE can be observed in all figures with increasing level of emotional resistance.

Figure 2 displays the simulated impact of emotional resistance on WTT CM for young, middle-aged and old participants. For an average emotional resistance of 3, the probability of WTT CM amounts to approximately 45% for old participants, 70% for young participants and 75% for middle-aged participants.

Different trends can be seen for WTE (Figure 3). Indeed, for an average emotional resistance of three, the probability of WTE CM amounts to approximately 30% for old participants, 55% for middle-aged participants and 70% for young participants.

These results demonstrate that emotional resistance has the most impact on willingness to try and to regularly eat CM for old people, and has the least impact to try CM for middle-aged people and has the least impact to regularly eat CM for young people.

For a low emotional resistance (value of one), the resulting probabilities of WTT amounted to a maximum of approximately 90% for all the participants working in different areas; assuming emotional resistance at the highest value of five, the resulting probabilities of WTT amounted to a minimum of 10% for people who were not scientists but work within the meat sector and of 45% for people who were scientists work outside the meat sector (Figure 4).

A larger effect of emotional resistance can be seen in Figure 5, according to the work area of respondents. People working outside the meat sector regardless they were scientists or not expressed the same WTE. With those participants, emotional resistance has the least impact on their WTE. Assuming emotional resistance at the lowest value of one, the resulting probabilities of WTE amounted to a maximum of approximately 85% for the participants working outside the meat sector, of 75% for scientists working in the meat sector and of 60% for people who were not scientists but working within the meat sector. Assuming emotional resistance at the highest value of five, the resulting probabilities of WTE

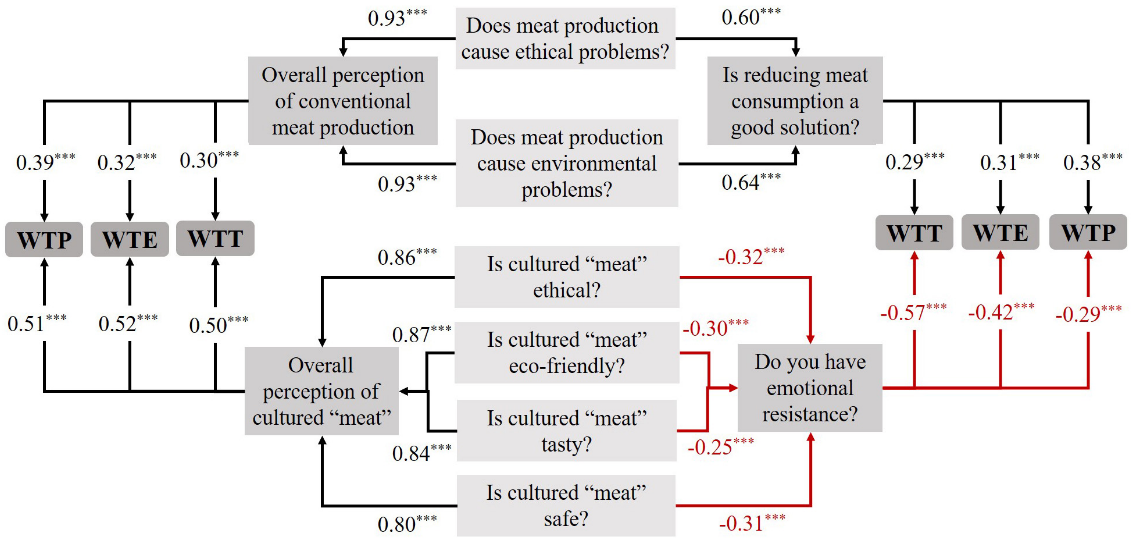

FIGURE 1

Correlation analysis between willingness to try (WTT), willingness to eat (WTE), willingness to pay (WTP) and overall perception of conventional meat production and cultured "meat" (CM). To have an overall perception of conventional meat production and CM, respectively, two overall variables "Overall perception of conventional meat production" and "Overall perception of CM" were created. Overall perception of conventional meat production was calculated by merging answers to two questions: (1) Does meat production cause ethical problems? and (2) Does meat production cause environmental problems? as follow (0.5 × answer to question 1 + 0.5 × answer to question 2) (both from a scale from 1 to 5). Overall perception of CM was calculated by merging answers to four questions: (1) How ethical do you think CM would be compared to conventional meat? (2) How eco-friendly do you think CM would be compared to conventional meat? (3) How healthy, safe and nutritional do you think CM would be compared to conventional meat? and (4) How tasty do you think CM would be compared to conventional meat? as follow (0.25 × answer to question 1 + 0.25 × answer to question 2 + 0.25 × answer to question 3 + 0.25 × answer to question 4). Positive correlations are presented in black, negative correlations are presented in red. ***Means that the correlation is significant at $p < 0.001$ level.

amounted to a minimum of 10% for people who were not scientists but work within the meat sector and of 15% for meat scientists and of 25% for those who work outside the meat sector.

Discussion

Perceptions and acceptance of CM in different countries

This survey translated into Italian, Spanish and Portuguese and distributed in countries in the South-West of Europe has provided novel results in addition to previous data from France (29), China (27) and Brazil (28). Emotional resistance associated to some food externalities (i.e., disgust, neophobia) is generally cultural dependent (32). Although people with origin from the South of Europe are known to be more conservative than Northern countries, the current respondents from Italy, Spain and Portugal seem to have a quite positive attitude towards CM (49% of the current sample considered CM as "promising and/or acceptable" and 29% perceived CM as "absurd and/or disgusting") when compared to the French participants (17% for "promising and/or acceptable" and 59% for "absurd and/or disgusting") (29), but less positive than Chinese and Brazilians, 15 and 18% of their samples perceived CM as "absurd and/or disgusting," respectively (27, 28; Table 6). With different sample sizes, the same proportion of respondents (33%) from the current samples and Brazilians had higher emotional resistance towards CM, which is expectedly, lower than the French proportion (56%) and higher than the Chinese proportion (16%) (Table 6). The emotional resistance may be associated to perceived immorality of innovation, distrust of new technologies, food neophobia (33), and also concerns about the decline and collapse of tradition (i.e., conventional livestock farming, traditional grazing landscape) (29).

However, even though the majority of current consumers from South-Western Europe have a more positive view of CM, and are more willing to try and eat it (around 66% WTT, 60% WTE), they are not willing to pay a premium for it (only 6% WTP more than conventional meat) as in France, Brazil and China (27–29). This is in line with the conclusion that positive perception is not necessarily predictive of the potential WTP for CM (34). For the time being, consumers still prefer conventional meat for the same price, even if CM is available at a significant discount (35). Although consumers are willing to try CM, when it comes to WTP, most prefer not to consume it (36, 37).

In overall terms, we found that the current respondents from the South-Western Europe have a similar level of acceptance of CM to those in Brazil, which is higher than those in France (50% WTT, 20% WTE, 8% WTP more) and even in China (50% WTT, 53% WTE, 4% WTP more) (Table 6). In general, Europeans are still reluctant to accept CM (38) compared to Americans (23, 39) and Chinese (27, 40). Especially in areas with a strong agricultural tradition such as France, they are particularly concerned about the origin and production process of agri-food (41). Meat alternatives including CM would be considered as ultra-processed food with safety concerns (41). According to the European consumers in the Netherlands, Poland, Spain, and

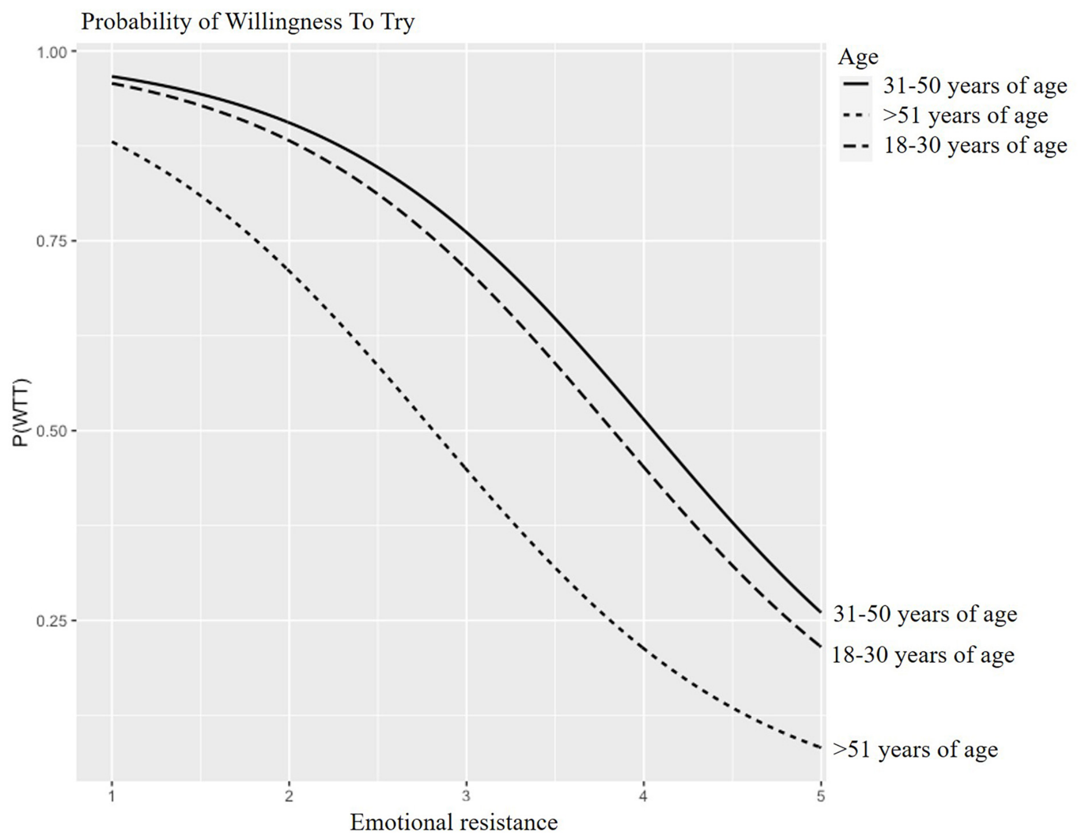

FIGURE 2
Predicted probability of willing to try (WTT) cultured "meat" (CM) depending on emotional resistance for different age participants.

Finland, and also the United Kingdom, CM was the least (6%) accepted protein alternative compared to plant-based (58%), single-cell (20%) and insect-based (9%) protein (42). Although sample sizes and demographics of respondents vary across studies, it seems that consumers from Germany, Italy, Spain and the Netherlands, for example, are more likely to accept CM than those from France and Belgium (29, 34, 43–46). We found that in our study, the current Spanish participants tend to accept CM more than the Italian and Portuguese ones. According to different comparative studies of consumer perception of CM, Spanish consumers had indeed higher trust and acceptance, and lower food neophobia and disgust towards CM than people from other European countries such as France, Germany, Sweden, and even UK and Brazil (47, 48), and it was reported that Spanish consumers would be ready to buy CM if it would be affordable (49). Comparing to the major European countries from the North that are leading the race such as the Netherlands, there are several CM start-ups currently operating in Spain and the Spanish government is also investing in the CM sector (50). These initiatives may boost citizen's awareness of CM from different angles. By comparison, Italy is where valuable indigenous cattle breeds are largely raised and is the country where the prestigious PDO [Protected Designation of Origin (food and wine)] and PGI [Protected Geographical Indication (food and wine)] are largely located. Italian cuisine has influenced gourmets across Europe and around the World (51). Meat consumption is therefore significant and important in Italy, despite the fact that Italians are increasingly sensitive to the negative effects of the conventional meat sector (51). In 2020, more than half of Italian consumers stated that they would reduce their meat consumption in order to meet the principles of ethical consumption and there are 8% Italians who chose a vegetarian diet and this number is continuously growing (52). The traditional consumption of meat and the influence of emerging trends will have a decisive impact on the acceptance of CM in Italy. Moreover, we found that the current respondents from the South-Western Europe have a similar level of acceptance of CM to those in Brazil, we assume that some common points (i.e., language, culture) between Brazil and Portugal might be able to explain part of the similar acceptance of CM.

Potential profile of CM adopters and rejectors

According to previous published results, the profiles for potential consumers of CM can be, on average, young and well-educated people, vegetarian, and aware of the technology of CM to some extent (22, 34, 35, 53). Our results confirm these observations since we found that young and higher educated people, also people who are familiar with CM would be more willing to accept CM (summary in **Table 7**). Notably, we found that people who work outside the meat sector and/or work in academia as scientists would be more willing to try, to eat and to pay more for CM.

With the current respondents, gender, age, origin and occupation have significant effects on the acceptance of CM. While

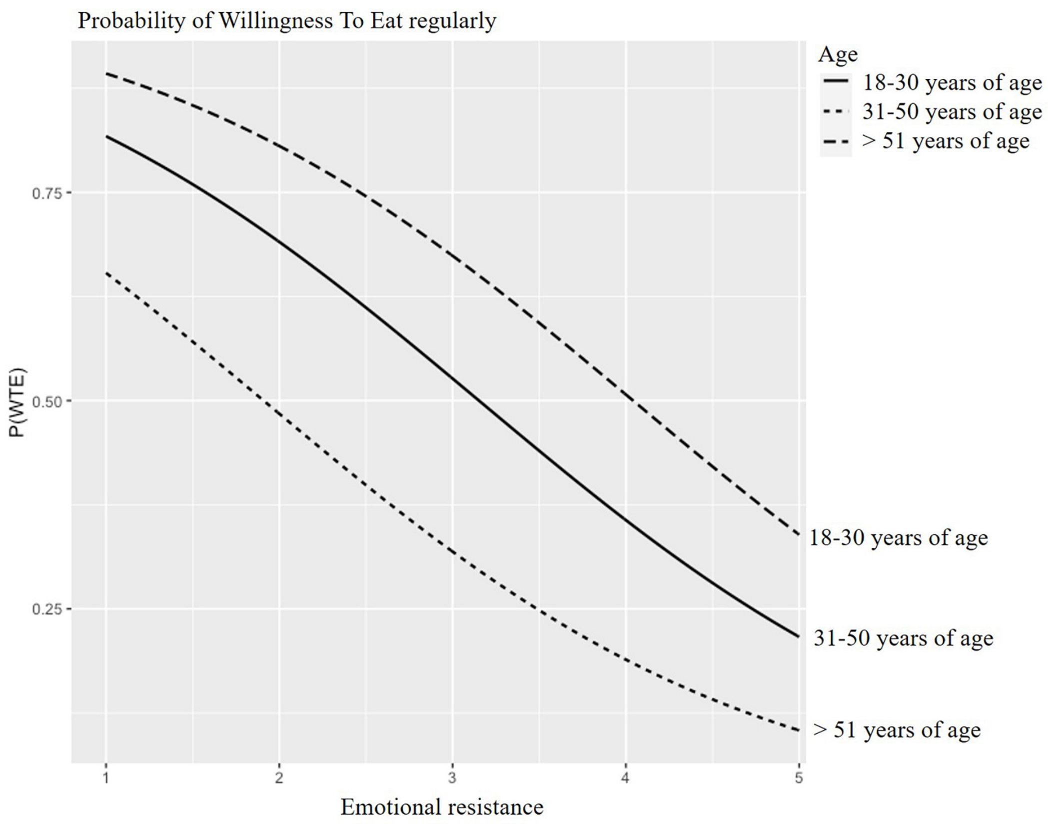

FIGURE 3
Predicted probability of willingness to eat regularly (WTE) cultured "meat" (CM) depending on emotional resistance for different age participants.

there is no doubt that people of 18–30 years of age had the highest acceptance of CM, 31–50 years middle-aged people also seem to have a higher willingness to try but not regularly eat compared to young people. Moreover, although there was no difference of WTT and WTE between females and males, we do notice that the possibility of WTT and WTE for males was significantly higher than females. Wilks et al. (54) found that the effect of age and gender are more important for acceptance than education level. This is consistent with our results. Indeed, despite that higher educated people had higher WTT than lower educated people, the predictive effect of education level is not significant in the logistic regression model.

Similarly, with the current respondents, meat consumption level is not a significant factor influencing CM acceptance, but we noticed that the current vegetarians and low meat eaters would be willing to pay more for CM than heavy meat eaters. This is in contrast with the finding that meat consumers rather than vegetarians/vegans seem to be willing to pay more for CM (34). However, it seems that there has always been controversy regarding vegetarian acceptance of CM depending on the motivations to adopt the vegetarian diet. In some studies, vegetarians were more likely to accept CM (23), but in others, vegetarians were less likely to consider the consumption of CM (55), due to concerns about such as healthiness and safety (45). Vegetarians may accept to eat CM to avoid slaughtering animals or may not accept to eat CM, because they refuse to eat any type of meat (including meat from cultured muscle cells). Therefore, it seems difficult to conclude about any effect of meat consumption level on potential CM acceptance.

Although those more familiar with CM had a higher WTT and WTE, the predictive effect of familiarity is not significant, which would suggest that it is unreliable to predict acceptance based merely on familiarity with CM. Nonetheless, we found that people who heard about CM tend to be more likely to try CM but less likely to consume it regularly. This may suggest that regular consumption of CM is unacceptable for consumers at the present stage, even if they are willing to try but maybe just due to curiosity. Anyhow, results from the literature are not consistent in this area: Rolland et al. (44) and Siegrist and Hartmann (48) observed that the previous knowledge of CM can be a good predictor of consumer acceptance, but, however, providing too many technical details to consumers may reduce consumer acceptance (48).

Bryant et al. (43) found that people who work in the sector of animal agriculture or meat production were more likely to accept CM. The associated explanation is that farmers may believe that CM can be an effective means of meeting increasing meat demands and of transitioning away from intensive industrial productions. As the authors mentioned, this might be counter-intuitive. Indeed, we may think that farmers would be opposed to a technology that is likely to replace their own professional activity (56). This can explain why we observed in our study that people working in the meat industry had the least willingness to accept CM. These people have a stronger emotional resistance towards CM. And, even if they have the same level of emotional resistance, those working in the

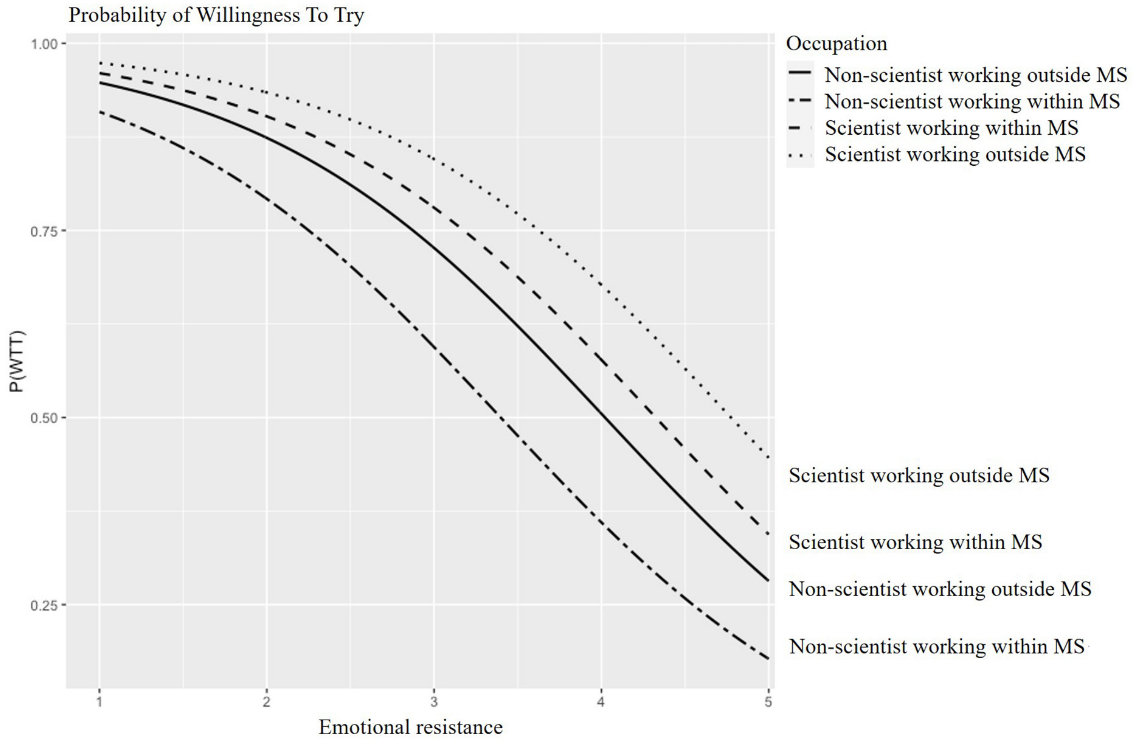

FIGURE 4
Predicted probability of willing to try (WTT) cultured "meat" (CM) depending on emotional resistance for participants working in different areas. MS, meat sector.

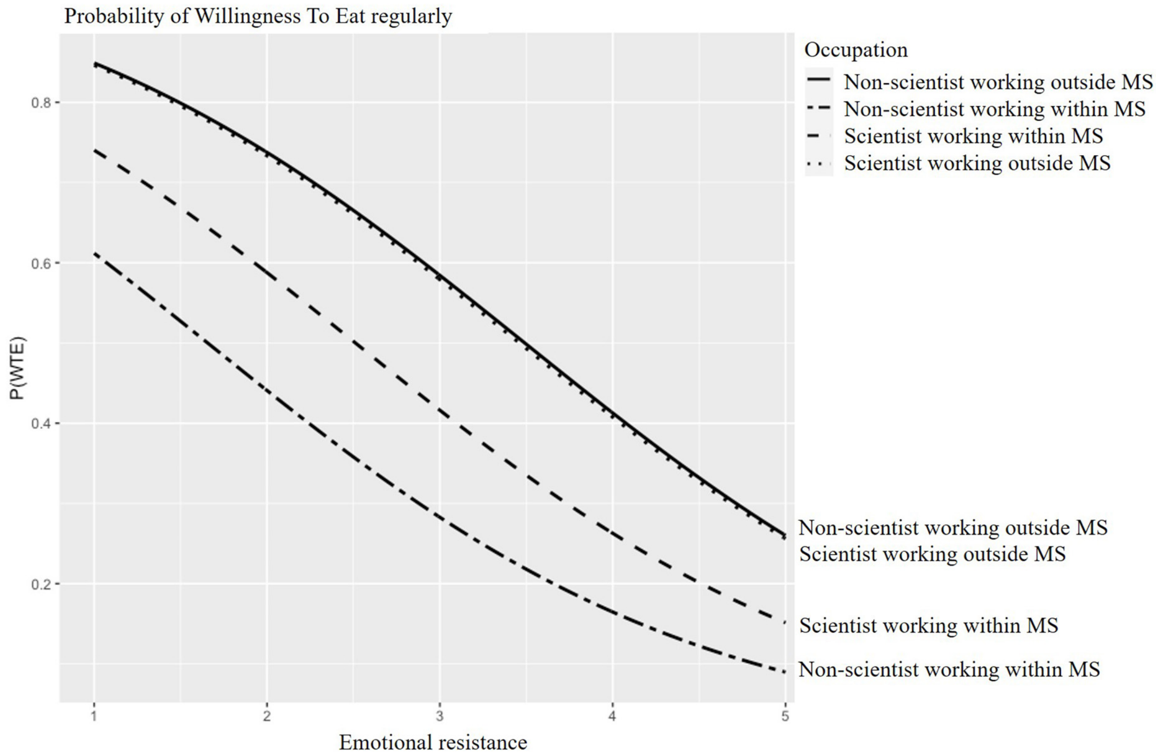

FIGURE 5
Predicted probability of willingness to eat regularly (WTE) cultured "meat" (CM) depending on emotional resistance for participants working in different areas. MS, meat sector.

meat sector have a lower WTT and WTE than those not working in the meat sector.

We also found that people working as scientists in academia were more willing to try, eat and pay more for CM. This is logical since people who work in the scientific area are likely to be more open to any technology. They might be also more aware of the principle of CM production, and they may know better the importance of technical expertise and financial investment required for innovation, so they are more willing to pay a premium. Their views on CM are more likely to be rational perceptions based on science and technology as opposed to emotional fear or disgust to something unknown on the one hand or to quick adherence to concepts disseminated on social networks on the other hand. Alternatively, scientists being mainly motivated by science and technology, their opinions regarding social consequences of the development of any technology might be less robust compared to stakeholders and politics.

The potential motives and barriers of the current acceptance of CM

Cultured "meat" has emerged in a period where the ethical, environmental, safety issues regarding conventional meat production have been subject to growing criticisms. To reach the goals of a sustainable meat production, CM aims at guaranteeing global food security while reducing animal suffering and preserving environmental resources (15). The potential benefits of producing meat *in vitro* have been advocated by CM proponents for a long time, including by some highly influential celebrities (i.e., Bill Gates). Under the influence of these privileged people and due to socially influential activities (such as the protests against animal slaughter and referendums on animal welfare and environmental protection), it may become politically correct to accept CM. In other words, with the constant propaganda about the advantages of CM and the disadvantages of conventional meat, to address environmental, ethical and safety problems that caused by conventional meat production, citizens awareness will be boosted, and they may have to end up by accepting CM. Hence, CM is indeed perceived as a promising new field. This can be seen in the large number of articles that continue to be published in the press media despite a low scientific background (57). Although CM can avoid mass slaughter and exploitation of animals (58), once reliance on fetal bovine serum is no longer necessary, this technology is perceived as ahead of morals. However, the fact that the production process does not fit with the current European law that meat should originate from animal flesh, not from cell culture is also a moral issue. This is also the origin of emotional resistance caused by food neophobia and disgust that has a negative effect on CM acceptance (48). Even leaving aside the different nature of producing meat in a conventional or artificial context, food fraud issue also deserves caution. As demonstrated by Treich (59), CM and conventional meat may become indistinguishable as technology is constantly and rapidly updated. In this way, conventional meat could be fraudulently substituted, which would cause threaten and challenges to consumer welfare and market regulation.

Weinrich et al. (46) found that ethical concern is a strong driver that affects consumer acceptance. In fact, we found that the concern of environment is as strong as ethics to affect consumer WTT and WTE CM (correlation coefficients between ethical, environmental concern and WTT are 0.24 and 0.27; with WTE are 0.37, 0.37, $p < 0.001$, summary in **Table 8**). As mentioned above, the advantages of CM in terms of animal welfare and environmental protection have been promoted for a long time, despite the latter at least is controversial (14) and need to be considered in depth. According to some authors, as the production of CM would be progressively optimized, much fewer resources (60) and energy might be required and more environmental-friendly and sustainable production could be achieved (61), but this is not clear yet (14). CM also requires no management of carcass waste and may have less transport and refrigeration costs and it is expected that CM should have a longer shelf life than conventional meat (13). However, at present, a large amount of energy is still needed to produce CM (i.e., ingredients producing, bioreactor running and post- processing, etc.). Therefore, the issues involving land use, energy use and carbon opportunity cost and their precise estimation are still key to determine the environmental benefits that CM could contribute at this stage (14, 62). In addition, CM generally produces less emissions than conventional meat, but more than plant-based meat substitutes (63) and it could cause even worse environmental damage in some scenarios. Indeed, emissions from CM production consist mainly of carbon dioxide, which will remain in the atmosphere for longer than methane and nitrous oxide, the main greenhouse gases emitted by conventional meat production (64). It is clear that the CM industry has put focus on a more sustainable production with improved efficiency on cost and resource use (15). As a consequence, the current trend seems to be that public trust is being gradually built up by the support of this innovation, before those environmental benefits are actually fully achieved. That is why it is still necessary to continue to carry out consumer acceptance studies, although it is difficult to anticipate and obtain precise data of future consumer acceptance. It is key to better understand the drivers and barriers of the perception of CM.

Our research shows that the overall perceptions of conventional meat production and CM have both significant impacts on the acceptance of CM. For the current respondents, the more they consider the conventional meat production causes serious ethical and environmental problems, the more they agree that reducing meat consumption could resolve these problems, the more likely they would be willing to try, to regularly eat and to pay for CM. Likewise, the more they believe CM can be ethical, eco-friendly, tasty and safe, the more likely they would be willing to accept CM. On the contrary, if people are less convinced that CM could be more ethical, eco-friendly, tasty and/or safe than conventional meat, this novel food technology, which is not yet widely available, would provoke higher emotional resistance, which would further result in more reluctance to accept CM, especially for the first attempts to try (since WTT is more correlated with emotional resistance than WTE and WTP). However, this observation is based on the current respondents, which are composed mainly of young and middle-aged people. The respondents of our sample are indeed younger than the actual populations of the studied countries. As it was demonstrated by Mancini and Antonioli (51), today young consumers' choices, based on more ethical principles, will contribute to shape the future market of meat and also of CM.

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TABLE 6 Perceptions and acceptance of cultured "meat" (CM) in different countries.

	Perception			Emotion	Willingness		
Country of origin	Promising and/or acceptable	Fun and/or intriguing	Absurd and/or disgusting	Resistance	WTT	WTE	Higher WTP
Italy, Spain, Portugal	49%	23%	29%	33%	66%	57%	6%
France[1]	17%	24%	59%	56%	51%	20%	8%
China[2]	36%	49%	15%	16%	50%	53%	4%
Brazil[3]	47%	35%	18%	33%	66%	60%	6%

[1]Data from Hocquette et al. (29).
[2]Data from Liu et al. (27).
[3]Data from Chriki et al. (28).

TABLE 7 Potential profile of cultured "meat" (CM) adopters and rejectors.

Potential profile of CM adopters	Potential profile of CM rejectors
Young	Old
Higher educated	Less educated
Familiar with CM technology	Not familiar with CM technology
Work outside the meat sector	Work within the meat sector
Scientist	Non-scientist

Moreover, the significant effects of age and occupation indicate that consumer acceptance of CM is highly affected by these two factors in addition to emotional resistance. According to logistic regression analysis, we do find that people different in age and occupations have different levels of emotional resistance and consequently various acceptance level of CM. Older people and people working in the meat sector, especially grassroots workers (i.e., non-scientists) are more likely to be emotionally resistant to CM and thus refuse to try and eat it. Conversely, young people and those working outside the meat sector, especially scientists, are more likely to be less emotionally resistant and more likely to accept CM.

Therefore, to give a more general conclusion based on the factors covered by our study, the negative impact of conventional meat and the positive impact of CM on issues that concern consumers (namely ethical and environmental issues) can be the motives of acceptance of CM. Conversely, issues for which CM may have weaknesses compared to conventional meat and emotional resistance would be the main barriers to accept CM. However, while these findings may be useful, they may be also biased, at least in part, by the lack of such products on the market and by the way information has been provided to respondents on the potential benefits or drawbacks of both conventional meat and CM. Overall, these findings provide insights into consumer perception and acceptance of CM that can be used by independent academia, and industries of conventional meat and CM. Not only consistent findings but also variabilities in the potential acceptance of CM by different consumer segments are important for the future communication on consumer study of CM. As it is highlighted by Faletar and Cerjak (65), the development and even success of CM in the current marketplace depends firstly on the advancement of the technology and how eco-friendly, ethically and economically the production process can be. However, it also mainly depends on the moral, ethical, economic perception consumers may have about this novel product and on their potential acceptance limited by some emotional resistance.

TABLE 8 Potential motives and barriers of cultured "meat" (CM) acceptance.

Potential motives of CM acceptance	Potential barriers of CM acceptance
Concerns about environmental impacts of livestock	Emotional resistance
Ethical concerns	Lower perception of CM benefits in terms of environmental and ethical impacts
A better understanding of CM technology and less knowledge in meat production	Less knowledge about CM technology and more knowledge in conventional meat production
A better understanding of science and technology in general	Lower education level and less understanding of science and technology
Perception that CM may be tasty, safe and healthy	Perception that CM may be not tasty, safe and healthy

Limitation concerning sampling and representativeness

In general, the sample collected for this study consisted of a slightly more female, young, middle-aged and Italian population. It is certainly the most rigorous and correct approach to collect demographically representative data for a questionnaire-type study. Nevertheless, are survey data that are less strictly representative can be effective to convey some useful information? In recent years, there has been a proliferation of research studies on CM, using sample data that are either representative of the local population (43) or not, which seem to be more often not representative (22, 31). However, through our research, as well as previous research and review articles (48), the perceptions and acceptance of CM among consumers with different origins and backgrounds, while not identical, but basically move up and down on the same trends. One of the essences of survey-type questionnaires is to reflect a certain trend through a large sample of data. Undoubtedly, the trend reflected by an extremely biased sample will also be extremely biased, which is definitely not our case. But it cannot be guaranteed that the results demonstrated by a strictly representative sample are completely accurate and representative. One of the purposes of this study is to reflect the overall consumer perception and acceptance of CM in three countries from South-Western Europe. Despite for the limitation of sampling and representativeness, comparing results obtained with the same experimental design between countries or between similar consumer segments could provide useful information.

Conclusion

Consumer acceptance is critical for the success of the CM industry. This study sheds light on how consumers from Italy, Spain, and Portugal perceive CM and their acceptance. In comparison with the previous data, the current Italian-, Spanish-, and Portuguese-speaking and/or originated people seem to have a more positive attitude towards CM especially compared with French samples. About a quarter of people have a negative view (absurd and/or disgusting) or emotional resistance towards CM. According to the current participants, the acceptance of CM tends to be higher for 18–30 years-old people and for respondents who work outside the meat sector especially scientists, and people who already heard about CM and with a higher acceptance for males. By comparison with respondents originated from Italy and Portugal, Spanish respondents seem also to have a higher propensity to accept CM. The high predictive effects of age and especially occupation indicate that these two factors can be good indicators of consumer acceptance of CM, which tends to be larger among young people and people working outside the meat sector.

Issues arising from conventional meat production that can be addressed by CM, for example with regard to animal welfare and the environment, can be among the major motives for the current respondents to try and regularly eat CM. For instance, according to proponents of the CM industry, the perceptions that CM may be more eco-friendly, ethical and healthy than conventional meat could motivate consumers to consume CM. On the opposite, price, the emotional resistance induced by CM and the negative impacts of CM for consumers (in terms of safety and healthiness for example) would be the barriers for the current respondents to accept CM.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ÉH, JL, M-PE-O, SC, and J-FH: conceptualization. JA, NR, and BP: data collection. JL: curation, formal analysis, and writing—original draft. JL and J-FH: investigation and methodology. M-PE-O, SC, and J-FH: supervision. JL, M-PE-O, SC, and J-FH: validation. JL, JA, NR, BP, ÉH, SC, M-PE-O, and J-FH: writing—review and editing. All authors read and agreed to the published version of the manuscript.

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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Non-animal-based options for animal-based foods- towards a systematic terminology

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The market has seen a rapid increase in animal-free products intended to replace animal-based foods due to concerns for human health and environmental sustainability. However, there is a lack of consistent terminology for these products, with various terms being used interchangeably, creating ambiguity. To address this issue, we propose a systematic nomenclature that defines the most commonly used terms, namely alternative, substitute, replacement, and analog, along with examples of each. In this nomenclature, a substitute primarily serves a culinary purpose, while a replacement is concerned with nutritional properties. An analog strives to satisfy both culinary and nutritional attributes to closely mimic animal-based foods in terms of sensory, nutritional, and functional characteristics. The term "alternative" serves as an umbrella term encompassing all possibilities. This work aims to promote a clearer understanding of such products and their intended use and facilitate a unified use of terminology across disciplines. This will also enable informed decision-making for consumers and greater transparency in the food industry. The health and environmental implications of these products are not discussed in this perspective.

KEYWORDS

alternative, substitute, replacement, analog, animal-based, plant-based

Introduction

The interest in animal-free products for animal-based foods has seen a remarkable surge in recent years driven by a combination of ethical, environmental, and health considerations. With the growth of plant-based meat, dairy, and protein market, small and large companies are turning to produce a new generation of animal-free choices that imitate the taste, texture, and appearance of traditional animal-based foods (1). The industry has experienced a rapid increase in demand (2), leading to technological advancements in creating non-animal-based products, particularly plant-based, imitating animal foods (1). In 2018, the market was valued at $4.6 billion, and some projections indicate that this figure is set to reach $85 billion by 2030 (3). As the popularity and production of these products increase, so does the need for understanding and education about them. New knowledge comes with new vocabulary or new usage of the existing vocabulary. However, the wide range of terms used to describe these products has used little or no consistency and systematicity, leading to ambiguity and uncertainty about them.

Regarding meat, our research based on the Web of Knowledge from 2000 to 2022 using "All Fields" found that the terms "meat alternative," "meat substitute," "meat analog or analogue," "imitation meat," "mock or fake meat," and "meat replacer or replacement" have been the primary terms used. Our findings show a sharp rise in using these terms in the scientific literature over the past decade compared to their negligible use before (Figure 1A). Among different terms, "meat analog" has been increasingly used over the years, followed by "meat substitute," "meat alternative," and "meat replacement." In this search formulation, some overestimation in the number of articles per term was unavoidable, as different terms may have been used within the same article. However, this does not change the remarkable increasing trend of emerging publications (4). In Figure 1B, we plotted the sum of the publication numbers for each term shown in Figure 1A and compared that with an "OR" formulation, where at least one term should exist in each publication. The difference indicates the increasing number of times several of these terms are being used within the same article. The figure shows the acceleration of this difference in the last few years. Moreover, most publications use different terms without distinction (3, 5–15). This lack of clear differentiation is also apparent in both mass and social media (15–17).

The synonymous use of words may serve some rhetorical purposes, such as enhancing readability and esthetics. However, in the realm of science, it is crucial to consistently use precise and unambiguous language to ensure clear and unified understanding. Given the abundance of non-animal-based food products available today, the lack of a distinct and purposeful differentiation represents at least a missed opportunity, calling for a well-defined language shared by different agents in the food system. In light of this, we suggest a definition for the most commonly used terms: "alternative," "substitute," "replacement," and "analog," along with examples of the products they represent. Such standardization is not only important for researchers, producers, and regulators in terms of health, food production, and labeling, but distinguishing between different options facilitates informed decision-making.

Terminology: foundation and definitions

Foundation

There are different dietary approaches to reducing the consumption of animal foods. The most common is choosing whole plant foods rich in protein or using other protein sources, such as plant-based meat/dairy, algae, fungi (e.g., mycoprotein), insects, or cultured meat. The plant-based products considered here entail algae and fungi as plant-like foods or ingredients. However, other options, such as insects and cultured meat, are not considered plant-based and, therefore, not discussed.

Before addressing the basis of the proposed terminology, it should be noted that the increasing demand for plant-based products as an option to animal foods is relevant in societies that primarily consume animal-based foods, such as the Western world. However, in communities where plant foods form the staple diet and animal products are consumed only occasionally, the idea of plant-based "alternatives" would be irrelevant.

The nutritional and culinary attributes are used as the basis for our definitions of the most commonly used terms, namely "substitute," "replacement," "analog," and "alternative."

The nutritional attribute considers the nutrients present in the plant-based products compared to their animal food counterpart when a nutritionally comparable plant-based option is sought for an

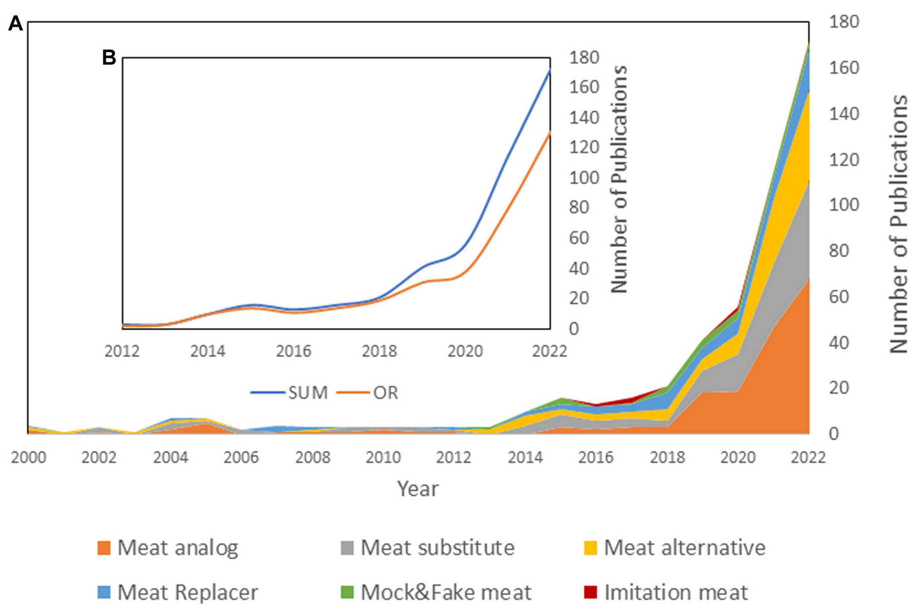

FIGURE 1
(A) The cumulative number of scientific publications reported by Web of Knowledge using "All Fields" containing the terms "meat alternative," "meat analog/analogue," "meat substitute," "imitation meat," "meat replacer/replacement," and "mock/fake meat"; [**(B)**, Inset] The sum of the number of publications containing the terms "meat alternative," "meat analog/analogue," "meat substitute," "imitation meat," "meat replacer/replacement," and "mock/fake meat" presented in **(A)** (SUM), and the number of publications that have used at least one of those terms (OR) from 2000 to 2022 reported by the Web of Knowledge using "All Fields."

animal-based food. Therefore, the selection is made based on the nutritional profile, which refers to the presence and quantity of key nutrients. In determining nutritional similarity, the key nutrients of a particular food, such as calcium in dairy or protein, iron, and zinc in meat, serve as the point of reference. The goal is a nutritionally comparable plant-based option to the animal-based counterpart.

The culinary attribute applies to artisanal, household, and industrial food preparation and production. The point of reference here would be the function of food, often used as an ingredient, as well as the sensory characteristics of the end product or the product itself if consumed alone. As for function in a recipe, the plant-based ingredient used in place of the animal food should have the same functional properties (e.g., thickening, foaming, emulsifying, stabilization, and gelling ability) to produce an end product with the same or very similar sensory qualities (2).

Proposed terminology

Substitute

A plant-based food or ingredient that can substitute the original animal-sourced food or ingredient outside or within a recipe. When used in a recipe, a substitute should be similar, if not identical, in its culinary properties to the original ingredient. As the physiochemical and biological properties of plant-based foods notably vary from those of animal foods, it is important to find those that match the functional attributes of the animal source ingredients to produce the same or similar end product. Therefore, understanding the fundamental qualities of both the original and the substituting ingredients is necessary. However, when substituting an animal-based food with a plant-based food outside a recipe, the gastronomic and sensory aspects take precedence over functionality. In both cases, the nutritional qualities are either not considered or become secondary.

Examples

- *Bean patties:* vegetarian or vegan burger patties made primarily from mashed beans, such as black beans, kidney beans, or chickpeas, along with other ingredients such as vegetables, grains, and spices. Bean burgers do not try to mimic the taste or texture of meat. Moreover, although they can be a good source of protein, they have an overall different nutrient profile than meat. However, they can be prepared to have a similar texture to beef burgers with similar cooking methods, such as grilling or pan-frying. In addition, they can be served on a bun with toppings such as lettuce, tomato, onion, cheese, and condiments such as ketchup or mustard, providing a similar sensory and gastronomic experience to a traditional beef burger.

- *Plant-based milks* (e.g., nut milks, oat milk, coconut milk, hemp milk): the nutritional values of these products vary from dairy milk (18), except for soymilk; however, they typically have physicochemical and sensory properties similar to cow's milk (1). Therefore, they can provide a culinary function and sensory experience similar to dairy milk. For example, they can substitute dairy milk in a "latte" or hot chocolate or be consumed alone. Nevertheless, some plant-based milks may not react the same way as dairy milk in certain cases, such as those that require heating and curdling of milk (1).

- *Vegetable oil:* they can be used as a substitute for butter in baking and/or cooking. Like butter, they contribute to tenderness.

- *Nuts:* although relatively high in fats (mainly unsaturated) and protein, they have a different overall nutrient composition than meat. Nevertheless, they can provide similar functionality and sensory properties as meat in various recipes. Walnuts, for example, can substitute meat to make walnut balls instead of meatballs. Similarly, nut loaves can replace meat loaves.

- *Aquafaba:* can be used as a substitute for egg white in baking (19). It is the water in which chickpeas and other legumes are cooked and has similar foaming and binding abilities to egg white (19).

- *Agar agar:* can be used as a substitute for gelatin in dishes like jellies, puddings, custard, and fruit gummies. It is extracted from red algae and has very similar gelling and stabilizing abilities as animal-sourced gelatin (20).

Replacement

Refers to a plant-based option with similar nutritional properties to its animal-based counterpart. The focus here is the key nutrients in the animal-based food or ingredient, and the functional and sensory attributes are secondary considerations. Therefore, the primary concern is the nutritional profile when seeking a plant-based replacement.

Examples

- *Tofu:* a minimally processed product made from soybeans that provides high-quality plant-based protein similar to animal protein (21). Although tofu's protein content is lower than meat, it is often used to replace animal protein due to its high quality and digestibility. It is also considered a reasonable source of some key nutrients such as calcium and iron (22).

- *Tempeh:* another soy product made from partially cooked, fermented soybeans (21). It is dense and chewy and can be used in stir-fries, burritos, sandwiches, soups, and other dishes. Tempeh is less processed than texturized vegetable protein (TVP) and tofu. However, fermentation improves its protein digestibility and mineral bioavailability compared to tofu (23), resulting in nutritional values compatible with meat. While 100 g of beef (ground, 85% lean meat / 15% fat, patty, cooked, broiled) contains about 26 g protein, 15.4 g lipids, 18 mg calcium, 2.6 mg iron, and 6.3 mg zinc, 100 g of tempeh contains about 20 g of protein, 11 g lipids, 111 mg calcium, 2.7 mg iron, and 1.1 mg zinc (24). Although the nutrient composition of tempeh can vary depending on the brand, it provides equivalent amounts, and sometimes more, of the key nutrients such as protein, fat, iron, and calcium and, therefore, can be used as a replacement for meat.

Analog

Refers to a plant-based product that intends to match both the nutritional and culinary attributes of its animal food counterpart. The aim is to re-create the original animal food in terms of appearance, texture, flavor, mouthfeel, and other sensory qualities while meeting its nutritional and functional properties. Thus, their production often requires extensive processing with a careful selection of ingredients and technologies compared to "substitutes" and "replacements."

Examples

- *Soymilk:* nutritionally, it is the closest to dairy milk (18, 25). It is the only plant-based milk with comparable amounts of protein, minerals, and vitamins to cow's milk (18). Additionally, it is often fortified with vitamins and minerals, such as vitamin D and calcium, to be nutritionally compatible with dairy milk (26, 27). Despite its "beany flavor" (27), it is placed under the analog category as it can also be used as a dairy substitute, therefore meeting both the nutritional and culinary criteria.

- *First-generation meat analogs:* plant-based food products designed to mimic the texture, taste, and appearance of meat. They were developed in the 1960s and 1970s and are typically made from soy, wheat, nuts, or products such as TVP. Their production was to meet the dietary needs of vegetarians and vegans who wanted to consume a meat-like product without consuming animal-based foods. However, the initial meat analogs produced through low-level processing techniques were criticized for their lack of taste and texture compared to real meat. Some examples include veggie burgers, different forms of vegetarian chicken such as nuggets and patties, vegetarian sausages or links, hot dogs, and cold cuts. Some famous producing brands include Worthington, Yves, MorningStar Farms, Loma Linda Foods, Lightlife, Tofurky, and Gardenburger.

- *Second-generation meat analogs:* a type of non-animal-based meat that aims to replicate the texture, flavor, and appearance of real meat more closely than earlier-generation products. Unlike the first-generation meat analogs, which were simply made from soy protein, wheat gluten, or nuts, second-generation meat analogs often use a combination of plant-based or plant-like ingredients, such as mycoprotein, and food technologies to mimic meat in its entirety. They require a larger number of additives and ingredients, a higher level of processing, and extensive technological advancements (28–30). Some examples include Beyond Meat and Impossible Foods. These products utilize soy, pea, and wheat as the primary protein source (31), along with coconut oil, potato starch, and other ingredients to create products that not only taste and cook like animal meat, but also resemble its nutrient profile (1).

Alternative

In the context of the present perspective, an alternative refers to a food option that does not attempt to replicate its animal-based counterpart's nutritional and culinary qualities. An alternative is simply a different choice that may have similar physical characteristics to the original animal-based food, such as texture or form (e.g., fluid or solid), and is gastronomically desirable to the consumer. However, it is not required to be equivalent in all other properties. Hence, as the definition of the word implies, it encompasses all possible options or "alternatives," making it the broadest category.

Examples

- Drinking apple juice instead of milk.
- Using avocado and nuts instead of cheese and salami as part of a charcuterie board.
- An entrée of pasta and vegetables instead of beef stew.

Few notes to consider

Although sparse literature was found using the terms fake meat and/or mock meat, we recommend refraining from using these expressions as they could be considered derogatory. As we progress from alternative to replacement or substitute to analog, there is an increase in technological requirements, inputs, and processing (e.g., edamame/beans < tofu/bean patties < Beyond Meat). Therefore, the criteria required to be met also become more stringent. While an alternative is not required to meet any specific criteria to replace the original animal food, except for being gastronomically satisfying to the consumer, the substitute must have comparable culinary properties, and the replacement must meet the nutritional qualities. The analogs, on the other hand, are expected to satisfy both nutritional and culinary characteristics and provide the same or very similar sensory experience.

Despite the industry's efforts, some nutritional properties of analogs remain different. For example, animal foods contain mainly saturated fat, while plants primarily have unsaturated fat and no cholesterol. In the case of meat, some food companies have incorporated plant-based sources of saturated fat, such as coconut oil, into their plant-based meat products to simulate the characteristics of real meat (1). Meanwhile, a plant-based analog that is identical to its animal food counterpart in all aspects has yet to be produced. Whether these efforts are desirable from the health and environmental perspectives is beyond the scope of this perspective.

It is important to note that the definitions presented here are not always mutually exclusive and can overlap (Figure 2). For instance, an analog can serve as a substitute, replacement, or alternative, but the reverse is not always the case. The term alternative has often been used in different platforms to refer to analogs (10); however, in precise terminology, it is simply a voluntary food choice and does not necessitate to fulfill the nutritional or culinary attributes of animal-sourced food. As the criteria for this category are not stringent, it encompasses a wide range of options, from those emulating the original food (analogs) to those that bear no resemblance. For instance, an alternative to meat can range from avocado, which only shares the physical characteristic of being solid, to tofu, which additionally meets some nutritional qualities, to second-generation meat analogs (e.g., Beyond Meat), which is the closest to meat not only in physical appearance and nutrient content, but also the sensory properties. Analogs, on the other hand, are innovative creations that require advanced technologies and are gaged by their all-aspect equivalence with the original food. It is worth re-mentioning that there is a varying degree of similarity to the original animal food regarding the nutritional and culinary characteristics among analog

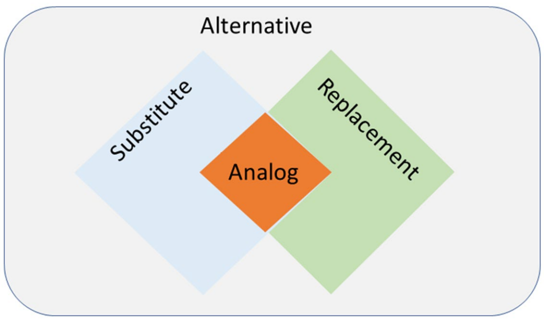

FIGURE 2
The overlapping nature of different terms describing various animal-free options for animal foods. The "alternative" is an all-inclusive term, "substitute" (culinary properties) and "replacement" (nutritional properties) overlap to give rise to "analog," which intends to imitate animal foods in terms of sensory qualities while meeting their nutritional and functional properties.

products, as it is a complex endeavor. However, their intention of production and use, often followed by a higher level of processing, places them in this category.

Discussion

Systematizing the nomenclature of animal food alternatives refers to organizing and standardizing the currently used names to describe them. Our goal is to make the existing terminology consistent and clear across different disciplines, cultures, and sectors. The current ambiguity in nomenclature is best highlighted in the definition of meat alternative given by Wikipedia: "A meat alternative or meat substitute (also called plant-based meat or fake meat, sometimes pejoratively) is a food product made from vegetarian or vegan ingredients, eaten as a replacement for meat" (32). The scientific literature also abounds with such statements (5, 7, 8). To present a brief review of the recent works, Knaapila et al. (33) state that food products crafted from protein-rich, non-animal sources, designed to resemble meat and be used instead of meat are commonly known as meat analogs, meat substitutes, or meat alternatives. While these terms are often used interchangeably in the literature (34), there can be variations in their specific definitions among different authors. In recent studies focusing on the production of such products using extrusion technology, the term meat analog has frequently been employed (31, 35–40). Some define meat analogs as replacers of meat and meat products in their functionality while being similar in terms of sensory properties, particularly taste, aroma, and texture, as well as nutritional value (41–43). Kumar et al. (44) define meat analog as "a food product that approximates the esthetic qualities and/or chemical characteristics of certain types of meat." Fiorentini et al. (8) state that "plant-based products with meat-like sensory attributes are often referred to as meat analogs, plant-based, or imitation meat." Banerjee et al. (45) state meat analogs are also imitation meat, since they imitate the esthetic qualities of regular animal meat in terms of texture, flavor, and appearance. Meat substitutes have been defined by Elzerman et al. (46) as products specifically developed to be consumed "instead" of meat. On the other hand, they defined meat alternatives as other products that are commonly consumed as protein sources in vegetarian meals, such as pulses and nuts. However, Choudhury et al. (47) considered plant-based meat alternatives as sustainable protein sources that can replicate "the taste, texture, color, and nutritional profile of specific types of meat."

Based on these studies, it is evident that a consensus regarding the terminology for these products has not been universally established (33). Therefore, to promote clarity and efficient communication within the plant-based food industry and among scientists, nutritionists, health professionals, consumers, and social media, we found it timely and appropriate to offer clear definitions for the commonly used terminology. This will help reduce confusion and improve understanding of the various plant-based options.

Sha et al. (4) have suggested that adhering to terms such as "meat alternative" rather than "meat analog" "would better serve the purpose of delivering sustainable protein supply," as plant-based protein products are unlikely to replace regular meat and poultry products. The authors argue that "by doing so, the industry would avoid many of the controversies and obstacles generated from the practice of mimicking animal meat and eliminate unnecessary consumer expectations. This approach would allow scientists and food processors to focus on the development of the best possible organoleptic and nutritious qualities of food from sustainable plant proteins to feed the ever-increasing global population." However, as "meat analog" is the most commonly used term, it would be impractical to eliminate it from the existing terminology. Moreover, despite the predicted increase in meat consumption (48), the rise in the production of these plant-based products is projected to continue as a response to their increasing demand (3). Additionally, the proposed definition of analog here considers both "organoleptic" and "nutritious" qualities, therefore, meeting the concern of the authors.

Moreover, we acknowledge the initiative by Plant Based Foods Association (PBFA) (49) to develop voluntary standards for labeling plant-based meats, milk, and yogurt in the United States. For meat, these labels include referencing the types of meat (e.g., meat, hamburger, sausage, chicken, pork) in terms of their flavor, texture, or style of preparation, the form or the type they take (e.g., nuggets, tenders, burger, patties), and qualifiers that indicate if the product is plant-based (i.e., consists mainly of ingredients derived from plants and does not contain animal ingredients of any kind), vegetarian (i.e., consists mainly of ingredients derived from plants but may contain small amounts of animal-derived ingredients, such as eggs or milk, but does not contain meat from any animal), or vegan (i.e., does not contain animal ingredients of any kind). While this information is necessary on a label, and we add that it should also contain the various additives, a systematic nomenclature is also needed at a higher level of classification that distinguishes between different terms.

In addition to our efforts, some plant-based food companies are working to standardize their product labeling to improve consumer comprehension and bolster marketing. Overall, systematizing the nomenclature for animal food alternatives is an ongoing process aimed at enhancing the precision and consistency of the terminology and facilitating greater understanding and transparency within different sectors.

Finally, the primary objective of this article is to enhance precision and consistency in the description of food components, fostering a shared understanding and transparency across various sectors. It is crucial to acknowledge that the dynamic nature of the food industry continually introduces new products to the market. As a result, our established terminology may not necessarily provide an unconditional fit for emerging and innovative food options. While this work serves as a valuable foundation, ongoing efforts are required to adapt and evolve the terminology to encompass these growing food products. By embracing the industry's dynamic nature and promoting continuing dialog and research, we can strive to ensure accurate and effective communication in the realm of food components.

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

NA and RS-S developed the content, drafted and edited the manuscript, and share the first authorship, JS developed the concept and content and edited the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that this work was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Halal cultivated meat: an untapped opportunity

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The global Halal food market is forecast to reach US$1.67 trillion by 2025, growing to meet the dietary demands of a rapidly increasing Muslim population, set to comprise 30% of the global population by mid-century. Meat consumption levels are increasing in many Muslim countries, with important implications for health and environmental sustainability. Alt protein products are currently being manufactured and positioned as one possible solution to reduce the environmental impact of meat consumption, yet, little is currently known about the Halal status of these products, nor the extent to which they appeal to Muslim consumers in emerging markets in Asia and Africa. Here, we explore key considerations regarding the acceptability of alt protein products for Muslim consumers, explore Halal certification requirements in the context of cultivated meat, and examine some unique beliefs within the Islamic faith that may support, as well as impede, widespread adoption of alt protein among the 2.8 billion Muslims of the future.

KEYWORDS

alternative protein, plant-based, halal, sustainable diet, cultivated meat and dairy

Introduction

The role that alternative ('alt') proteins, particularly alt meat, will play in transitioning the world's population to more sustainable eating patterns is hotly debated. Some commentators suggest that investment in alt protein technologies can reduce greenhouse gas (GHG) emissions over 11 times more than other green technology investments (1). However, others are more skeptical about these numbers, and are concerned that the emissions reduction potential of alt protein will be limited by its inability to displace meat and dairy products in peoples' diets.

Fermented, hybrid or cultivated (i.e., cell-based or cell-cultured) proteins (see Table 1 for definitions and examples) are entirely new concepts to many consumers, and are viewed with hesitation, citing concerns about naturalness, healthiness, compliance with dietary requirements, and overall safety (3). As a result, to benefit climate and biodiversity in a meaningful way, companies that produce and market alt proteins must carefully consider how to address consumer reticence. The overriding goal here is to promote habitual purchasing, beyond initial hype, and encourage direct substitution of animal-based products (4). This will be a complex task given that our diets have otherwise been shaped over millennia by a huge range of factors, including local culture, climate, agricultural practices, the food industry, trade, social relations and belief systems.

Here, we explore religious belief as one highly influential, yet often overlooked factor that influences the food choices of billions worldwide. At present, around 85% of the global population identify with a particular religion (5), many of which issue clear guidance on the

TABLE 1 Definitions and examples of different types of alternative protein, reproduced from Hajat and Parkin (2).

Name	Brief description	Example
Plant-based	These products use plant-based ingredients, such as beans, peas, lentils, and soy to create meat substitute products.	One market leader is Beyond Meat, which produces burgers and sausages from pea, mung and fava beans and brown rice. Beetroot and apple extract are added to mimic the coloring of meat.
Cultivated meat	*In vitro* laboratory grown meat from cultured cells. Also known as cell-cultivated, cell-based or cell-cultured meat.	The first ever commercial sale of cultivated meat was by an American start-up, Eat Just, in 2013, served in a restaurant in Singapore. Whilst still not widely available in many regions, there are rapid developments in this industry. Companies producing these products include Memphis Meat and Mosa Meats Inc.
Fermentation-derived processes	Traditional fermentation uses microbial anaerobic digestion to improve the taste or functionality of plant-based ingredients. Biomass fermentation involve the rapid growth of microorganisms which form the basis of the product Precision fermentation uses microorganisms as hosts to produce specific ingredients used in alt-meat.	Soybeans are fermented into tempeh. Mycoprotien Quorn is made from fermenting fungal spores. The heme protein (soy leghemoglobin) added to the Impossible Food burger to improve its distinctive meaty flavor.
Hybrid products	Produced by combining reduced portions of animal-based meat, or cultivated ingredients (i.e., fat) with plant-based ingredients.	The Rebel Meat 'semi- vegetarian' burger contains 50% beef and 50% plant-based ingredients.
Insects	Processed edible insects, consumed either whole or ground, and used as ingredients to enhance the nutrient profile of existing products.	Fazer, a Finnish company that manufactures bread using cricket flour, and Eat Grub produce energy bars enriched with cricket powder.
Algae	Processed edible algae, mainly used as food ingredients or dietary supplements.	Examples include Spirulina or Chlorella.

types of food considered acceptable to eat. Examples include the vegetarian diet recommended for Hindus, Buddhists and Jains, Islam's guidance on Halal and Haram foods, and the Jewish Kosher diet, amongst others. Despite such ubiquity, the role that religious beliefs play in shaping food choices is often neglected by companies developing and manufacturing novel foods. This represents a considerable missed opportunity, especially in the context of the Islamic faith, as we explore below.

The Muslim market for meat

The global Muslim population is predicted to grow to 2.8 billion people by mid-century, comprising around 30% of the world's population, with most of this expansion occurring in Asia and Africa (6). By then, it is estimated that India, a Hindu majority country, will be home to an estimated 310 million followers, the most of any nation in the world (6). By contrast, most investment and research into alt protein has so far occurred in the United States (US), which is a majority Christian country with a secular innovation ecosystem, followed by Israel, which is primarily Jewish (7).

The projected increase in the world's Muslim population in Asia and Africa will likely coincide with economic transitions in these regions. Rising income levels tend to lead to dietary changes as more people consume higher value foods, usually those rich in animal protein (8). This is demonstrated in Figure 1, which displays the countries that are estimated to be home to the largest Muslim populations by 2030, and projected changes in meat consumption (i.e., sheep, beef, veal and poultry, combined), from baseline year 2023 (9). Relative increases in meat intake range from 3 to 17%, are highest in India (noting the lower baseline meat consumption level in this country), with only Nigeria registering a decrease from 2023 consumption levels.

The halal market and dietary requirements

Adherents to Islam are asked to follow a 'Halal' diet, which refers to consumption of food and drink consistent with Islamic dietary laws. Box 1, below, outlines Halal requirements, with meat a major focus area. This guidance states that animals must be slaughtered in a prescribed way, and certain types of meat and by-products – including pork and blood products – eschewed. To support Muslims to follow a Halal diet, acceptable foods are certified by different Islamic bodies around the world. These organizations work to ensure that all aspects of production meet necessary requirements, additives and preservatives are Halal compliant, and that meat products have been derived from permissible animals that are slaughtered according to Islamic guidelines (10).

The global Halal food market was valued at US$ 1.27 trillion in 2021 and is forecast to grow, reaching US$ 1.67 trillion by 2025 (for context, global Kosher market revenue was under US$ 20 billion in 2021) (11, 12). In 2020, the trading bloc known as the Organization of Islamic Cooperation (OIC) reported a Halal food export deficit of around US$ 67 billion, indicating strong reliance on imports into major Muslim markets. The greatest volume of this trade comes from non-Muslim producer countries Brazil, India, the US and Russia. Here, technologies that ensure traceability of imported products are essential for consumer trust, and innovation in this area is growing. Most recently, this has included blockchain-enabled platforms to track the origin of Halal meat, and DNA testing kits to ensure

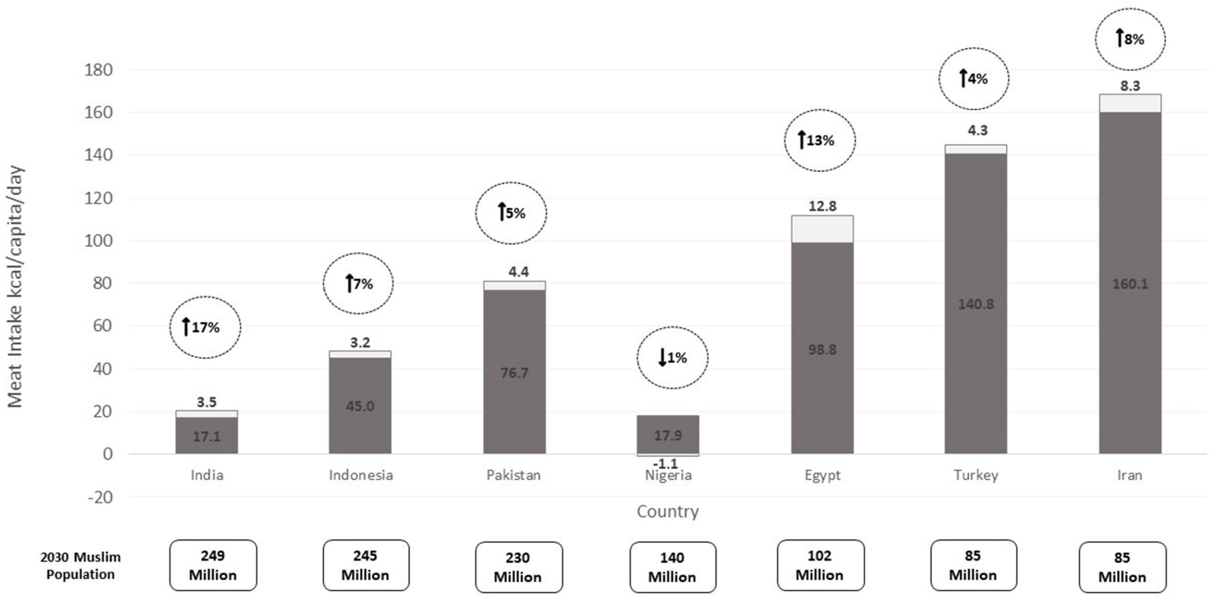

FIGURE 1
Projected change in meat intake in the most populous Muslim countries by 2030. Data from the OECD FAO Agricultural Output 2022–2023 (9); estimated percentage (%) increase in kcal/capita/day of beef, veal, sheep and poultry meat for the entire population between 2023 and 2030. Non-halal pig meat excluded as default. Population estimates for different religious group sin 2030 provide by Pew Research Centre (6) To note, no baseline data is currently available to estimate changes in meat intake in Bangladesh, Afghanistan, and Iraq – predicted to be home to the world's 4th, 9th, and 10th largest Muslim populations by 2030.

imported meat has not been tainted with forbidden animal-based products (13).

Trade imbalance represents a potential food security risk for many Halal markets. This is particularly true for Muslim-majority countries in the Gulf region which, due to climate and terrain, have limited capacity for in-country livestock farming and agriculture to meet national demand, and currently import over 85% of their food and around 62% of their meat (14). As such, alt proteins are not only being considered as potential solutions to climate change, but, if locally produced, can also support national food security goals alongside

BOX 1: Halal Dietary Guidelines.

- Meat from animals that are permissible and slaughtered in the prescribed way by mentioning the name of Allah (and no other gods or persons)
- Free from any part (or substance) taken or extracted from animals forbidden to be consumed by Muslims.
- Free from any substance declared as unclean according to Islamic law (including products considered to be contaminated with filth*)
- Prepared, processed, produced, or manufactured using utensils, equipment, and/or machinery which are free from any substance declared as unclean according to Islamic law.
- Not contaminated by any food or materials during preparation, processing or storage that do not fulfil the above requirements.
- Plants – all types of plants and their products or derivatives are Halal and can be eaten except if poisonous, intoxicating, and harmful to human health.
- Drinks – all forms of water are Halal, except if poisonous, contain Haram materials, are intoxicating or are harmful to human health. Alcoholic and intoxicating drinks are forbidden. Water mixed with filthy liquids or food laced with wine and alcohol are also not permissible.
- Arising from the idea of 'clean' is the concept of 'tayyib', which refers to good, pleasant, wholesome, agreeable and delicious, as opposed to 'khabith', which refers to impure, harmful and disgusting. Upholding the requirement of 'tayyib' in the processing of food includes maximizing hygiene and minimizing contamination.

*Filth, according to Islamic law, includes substances such as pork, blood and carcasses (carrion) which are filth by themselves and cannot be accepted as clean. It also includes otherwise clean substances that are contaminated by filth Adapted from Amabli et al. (16).

other innovations like vertical, urban and seawater farming, genetically modified crops and precision agriculture (15).

Addressing ethical and religious concerns

If alt protein companies are to succeed in attracting a substantial share of the global Muslim meat market, a fundamental question is whether different types of alt protein can even be certified as Halal. Whilst generally unproblematic from the perspective of 100% plant-based meat analogs, cultivated and hybrid products contain cells derived directly from animals. As yet, no clear guidance has been issued by any Halal certification body regarding the status of these products.

When attempting to address this point, scholars have considered various perspectives; for example, some have argued that cultivated meat contravenes Islam's 'Natural Law', as the production process can be seen as 'playing God' (17). Further complications arise from the fact that cultivated meat was originally intended to be made from cells harvested from live animals, rather than those slaughtered. This implies that the resulting cultivated product may not be Halal, unless cells were extracted from a permissible animal slaughtered according to Islamic guidance (17). Indeed, this is one of six key principles that a recent review on the topic suggests must be met in order that cultivated meat can be considered Halal, and is arguably one of the most important hurdles to overcome if cultivated meat products are deemed acceptable for Muslims to eat [see Kashim et al. (18) for an in-depth perspective on this issue]. In his book on animal welfare in Islam, Masri reported that extracting parts of live animals to eat was considered a delicacy in pre-Islamic Arabia, but the practice was subsequently outlawed by the Prophet Mohammed (PBUH) (19).

Another issue of concern for Muslim consumers is the use of cell culture media that are inconsistent with Halal laws. For instance, in many cases, the media in which extracted cells are developed contains fetal bovine serum, which is post-clotted blood fluid obtained from unborn cattle. Blood is considered unclean according to Islamic scriptures [Quran 5:3], and this point has been specifically highlighted by the Malaysian Halal standard (MS 1500/2019) (20). More recently, however, wholly plant-based media have been developed, helping allay the concerns of Halal consumers regarding fetal bovine serum, as well as addressing the requirements of other consumer segments, such as ethical vegans and vegetarians (21).

Similarly, some of the concerns around the acceptability of cultivated meat for Muslim consumers are shared by devotees of other religions. For Jewish consumers who follow Kosher guidance, the Chief Rabbi in Israel ruled for the first time in January 2023 that cultivated steak could be considered a Kosher product (22). This represents one of the first steps toward cultivated foods receiving widespread Kosher certification in the country, and is pivotal move for Israel, which is already home to 57 alt protein start-ups and has declared food technology a national research priority (7). The extent to which similar conclusions will be arrived at by Islamic religious leaders remains to be determined. In 2022, the Assembly of Muslim Jurists of America deemed cultivated meat provisionally permissible by default, provided that the above-mentioned Halal criteria are met. However, an ultimate ruling on the issue will depend on how the technology develops in relation to the source of used stem-cells, additives and the broader health impacts of these products (23). We note that investment in these technologies is also a priority for Muslim competitive markets in the Middle East, particularly the United Arab Emirates (UAE) (24). Abu Dhabi launched their Xprize 'Feed the Next Billion' initiative to specifically fund research into development of alt proteins the country (25), and the Middle East's first plant-based meat factory recently opened in Dubai (26).

Other factors influencing alt protein adoption in Muslim markets

If and when the issue of Halal certification is resolved, the question of how to boost the appeal of alt proteins to Muslim consumers still remains. Relatively little research exploring Muslim consumers' perceptions of alt protein is currently available, although the data that does exist suggests potentially greater willingness to try these products compared to non-Muslim consumers (27). For example, one recent study comparing the preferences of British Muslim and Non-Muslim consumers found significantly greater willingness to purchase cultivated meat amongst Muslim consumers, and greater willingness to pay extra for these novel products (28).

Muslims consumers otherwise share many of the same perceived barriers and facilitators to eating alt protein as are observed in other consumer groups across a wide range of countries (28). For example, where research has been conducted, acceptance of novel proteins, particularly cultivated meat, tends to be higher when consumers are more familiar with these products, have lower food neophobia scores, when they taste better, are more affordable, and when consumers are informed of their potential health and environmental benefits compared to traditional meat and dairy (3, 28).

Additionally, there is a range of more specific factors unique to Muslim consumers that are relevant to consider. For example, given that plant-based, hybrid and cultivated products can all be produced in highly controlled environments, this may limit the potential for contamination with non-Halal animal ingredients during production, thereby overcoming fears around product impurity. This is especially likely for cultivated products if the manufacturing process is reviewed and certified by a credible Halal authority that Muslim consumers already know and trust (29).

Availability of plant-based meat alternatives may also circumvent the issue of whether meat should be stunned prior to slaughter, which is generally considered more humane, but some believe is inconsistent with Halal rules (30, 31). Although Islam emphasizes the importance of animal welfare before and throughout the slaughter process, modern farming practices may fail to maintain these principles. As a result, consumers looking for Halal products that ensure animal welfare may be left with few options. More broadly, other qualitative research has revealed that some Muslim consumers recognize additional potential benefits of cultivated meat for the Halal economy, both in terms creating new jobs for halal meat scientists, as well as helping to grow Muslim-owned food businesses (29). Greater adoption of cultivated meat may also be viewed by some Islamic jurists and Halal consumers as a step toward Khilafa (guardianship of nature)[Quran 10:14], which is an important principle related to environmental sustainability. Here, Islamic law states that any new rulings must align with the objective of attaining welfare and warding off harm. As such, the adoption of a diet with a lower environmental impact, *via* consumption of alt protein products, may be considered a way to uphold at least two of the five key principles: the preservation of life and linage.

We also note various other well-known Islamic teachings with implications for health and diet, which may also support movement away from excess meat consumption in Muslim populations. These include the recommendation to avoid wasting food (i.e., *"Eat and drink and do not waste, for God does not love the wasteful."*[Quran 7:31]), and the Hadeeth (Prophet's saying) to moderate intake (i.e., "*No child of Adam fills a container worse than his stomach. A few morsels that keep his back upright are sufficient for him. If he has to, then he should keep one-third for food, one-third for drink and one third for his breathing*." [Jami` at-Tirmidhi (2380), Volume 37, Hadith 77]). In addition, regular fasting is also encouraged, as is taking care of one's body, as per the saying of the Prophet in response to one of his companions fasting daily *"… your body has a right over you"* [Sahih Al-Bukhari (1977), Volume 30, Hadith 198].

Academic research has proven that religiosity can play a significant role in promoting behavior change, including pro-environmental actions. For example, a recent study by Hassan et al. found that Muslim diners were keen to avoid wasting food to adhere to teachings within the Quran (32). As such, influential Muslims, including Islamic religious leaders, have potential to play an extremely important role in encouraging sustainable and healthy behavioral change, and should be included as key stakeholders in the sustainable diets movement in any Muslim majority country where this is a priority national agenda item (33, 34).

Conclusion

Muslim consumers' concerns regarding alt protein are currently poorly understood and rarely addressed by manufacturers of alt protein products. This is despite tremendous potential for market adoption, given the rapid growth and dietary transition occurring in many Muslim populations worldwide. In this piece, we outline key questions that require answering before widespread adoption of alt proteins is likely in Muslim countries. We also recommend further research to address religion-specific barriers to uptake. As decisions made by the Chief Rabbi in Israel attest, religious organizations and leaders can play a vital role in clarifying faith-related concerns about novel foods, helping to encourage vast numbers of followers to adopt more sustainable diets while remaining adherent to the core tenets of their belief systems.

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

SA and CH conceived of the article idea. SA contributed as lead authorship. SJ, EA, AF, and CH contributed to writing the final perspective piece. SA edited and formatted the manuscript for submission. All authors contributed to the article and approved the submitted version.

Conflict of interest

AF works as Halal Sector Senior Manager at the Agriculture and Horticulture Development Board (AHDB) (UK).

The remaining 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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Barriers associated with pulse and plant-based meat alternative consumption across sociodemographic groups: a Capability, Opportunity, Motivation, Behaviour model approach

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Introduction: To enhance environmental sustainability and food security, there should be a change in dietary protein consumption. It is suggested that meat consumption should be reduced and that the currently low consumption of pulses and other plant-based proteins should increase. We aimed to examine (1) how sociodemographic factors and perceived barriers are associated with self-reported current and perceived future pulse and other plant-based meat alternative (PBMA) consumption and (2) how sociodemographic factors relate to perceived barriers.

Methods: Participants were 18–75 year-old Finnish adults (n = 1,000). Multivariable logistic regression was used as the main analysis technique. The results were interpreted by employing the Capability, Opportunity, Motivation, Behaviour (COM-B) model.

Results: Pulses were consumed more often than PBMAs and lower education level and financial strain were associated with more infrequent pulse and PBMA use. The most common perceived barriers for pulse consumption were unfamiliarity, expensive price, and unpleasant taste, which can be interpreted to represent the capability, opportunity and motivation components of the COM-B model, respectively. Women, the young, and financially strained perceived more barriers limiting their pulse consumption than others.

Discussion: To increase plant-based food consumption, it is important that tasty, easy to use and affordable plant-based foods are available for all. Additionally, we suggest that food services should be encouraged to increase the use of pulses in their dishes and that capabilities, opportunities and motivations are taken into account in intervention measures advancing plant protein consumption.

KEYWORDS

plant-based diet, alternative protein, legume, socioeconomic differences, COM-B

1. Introduction

As the world faces new and recurring challenges, such as the climate change and the ever-growing global population, it is more important than ever to rethink the sustainability of our dietary and food production practices. Current high level of meat production is regarded as environmentally unsustainable (1), and plant-based proteins have generally smaller environmental footprint than animal proteins (2, 3). Despite this, meat consumption has increased significantly globally in the last decades (4). Cultivating more sustainable protein sources, such as pulses, can contribute to mitigating climate change (5), but it is also noteworthy to recognize that pulse cultivation is not unproblematic either [e.g., (6)]. Despite the shortcomings of pulse cultivation, it is widely acknowledged that there should be a transformation in dietary protein sources: for instance, in 2019 the EAT-Lancet Commission proposed a substantial increase in pulse consumption while reducing meat consumption to ensure global food production and healthy diets within planetary boundaries (7).

Meat has been regarded as a central ingredient in main meals especially in Western diets (8), while the consumption of pulses is generally low; for example, in Finland about 140 grams weekly (9), which is well below the recommended 525 grams weekly as suggested by the EAT-Lancet Commission (7). One reason behind this is that different sociodemographic groups often experience different kinds of barriers related to eating pulses – a relationship that needs to be better understood to increase the environmental sustainability of food consumption. Furthermore, a recent review on meat alternatives by Onwezen et al. (10) suggests that more research on pulse and plant-based meat alternative (PBMA) consumption is needed, as only 18 of the 91 articles reviewed concerned pulses or PBMAs.

In this paper, we examine how the barriers and sociodemographic factors are associated with current and future pulse and PBMA consumption, as well as how sociodemographic factors relate to these barriers. The conceptualization of the Capability, Opportunity, Motivation, Behaviour (COM-B) model (11) is applied in examining the barriers affecting plant-based food consumption. In addition, sociodemographic characteristics such as gender, age, education and income level are taken into account in the analysis, as they may be reflected on an individual's capabilities, opportunities and motivations to consume plant-based foods.

2. Applying the COM-B model in the context of plant-based eating across sociodemographic groups

2.1. Sociodemographics and barriers: selecting plant-based foods

In everyday life, food selection is often a routinized process. However, many economic, environmental, social, psychological and cultural factors are involved in why people eat the way they do (12). If one is accustomed to consuming meat at most meals, it may be difficult to alter such routinized ways of eating. Furthermore, a variety of societal and cultural practices maintain a meat-eating culture. For instance, meat is readily available at grocery stores, and restaurants are usually assumed to offer meat dishes, unless they are profiled as vegetarian or vegan. Furthermore, liking the taste of meat, the price of meat alternatives and the routinized nature of meat eating are significant barriers for reducing meat consumption (13). Skórska et al. (14) discovered that as a large part of Western cooking recipes center around meat, consumers are steered towards meat instead of plant-based protein sources.

Before and in the beginning of the 20th century, meat consumption in Finland was quite scarce, and pulses together with grains were an important source of protein (15, 16). After World War II, meat has had an important role in the Finnish food culture with most people consuming it regularly [e.g., (17)], and a significant amount of the Finnish population consume red and processed meat more than the national nutrition guidelines recommend (9). However, in recent years the consumption of all types of meat (beef, pork, poultry, game) has been decreasing slowly (18). The recently published Nordic Nutrition Recommendations 2023 advocate more plant-based diets by decreasing the amount of meat and increasing the consumption of pulses (19).

As meat consumption has already been decreasing and more plant-based diets are called for, it is an opportune time to try to quench the cultural appeal of meat by replacing it with pulse and other plant-based alternatives. Soy protein granules and tofu may be the most traditional and well-known meat alternatives, but in recent years different plant-based patties, sausages as well as various other forms of meat-like products have fast gained shelf-space in supermarkets (20). Such new products often imitate meat in sensory properties, like mouthfeel and taste (21), which often helps consumers to accept them as they provide a familiar alternative. In this paper we use the abbreviation "PBMA" to refer to all (processed) plant-based meat alternatives. The concepts of "plant protein food" and "plant-based food" include the aforementioned PBMAs as well as all other kinds of plant protein sources, such as fresh, dried and canned beans and peas.

Earlier studies have found typical pulse consumers to be young and women with a higher education, interested in healthy eating and living in large or medium-sized cities (14, 22, 23), and more sustainable eaters to be women, young, and highly educated (24). Furthermore, current consumers of pulses and pulse-based meat alternatives are also interested in consuming them more in the future (25, 26). Men, people with higher income, lower education level and disinterest in healthy eating gravitate more towards animal protein source consumption (13, 22, 23, 27, 28).

Major reasons for not consuming pulses are not being used to eating them, not knowing recipes for preparing them and not being interested in them (29). Additional barriers to pulse consumption found are, i.e., unpleasant gut symptoms (29), inconvenience and long preparation times (28, 30), inability to cook pulses and scarce number of traditional meals containing them (14) and the unpleasant taste of beans (25, 29, 31). Mäkiniemi and Vainio (32) found that price was the most decisive barrier to climate-friendly food selection, including increasing plant protein food consumption. However, there is as of yet little research on the association between sociodemographic factors and pulse consumption barriers [see (33)]. Our paper examines this relationship.

2.2. The COM-B model and plant-based eating

The COM-B model, developed by Michie, van Stralen, and West (11), provides a fruitful theoretic background for examining different habits, such as exercising, smoking and, as in this paper, eating. Furthermore, the COM-B model forms the center of the Behaviour Change Wheel (BCW) (11), which enables the planning of effective behavior change interventions. The COM-B model is a rather simple yet comprehensive system to analyze the different capabilities (C), opportunities (O) and motivations (M) people have for acting the way they do, and how these three components in turn may influence (and be influenced by) actual behavior (B). The COM-B model and BCW are effective in identifying how and which components should be transformed in order to achieve the desired behavior change. All three COM factors are required to be present for a behavior to occur, and for a behavior to change, as the factors interact with each other (11). As an example, if one enjoys plant-based foods and is thus motivated to consume them, but lacks the skills to cook such dishes and at the same time the selection of products is narrow or non-existent meaning that capability and opportunity are absent, one is not very likely to commit to a plant-based diet and motivation to do so may decrease as well [see (34)].

Michie et al. (11) define all three COM-B factors as comprising of two dimensions. Capability is divided into *physical and psychological capability*. In the context of eating, physical capability may refer to the bodily ability to cook, and psychological capability being able to understand recipes and how to modify them. Opportunity consists of *social opportunity*, which can be defined as the surrounding social environment, and the *physical opportunity* concerning which food items are on offer and their affordability. Motivation includes *reflective motivation* such as planning what will be eaten and for what reasons (e.g., health, environment), and *automatic motivation* that takes into account emotions and impulses, like smelling something good and suddenly wanting to eat that even though something else was previously planned – thus overriding the reflective motivation.

The BCW, and the COM-B model in its center, offers a suitable framework for planning (eating) behavior change interventions, since it takes into account both the inner and outer behavior cues. The intervention measures presented in the BCW are closely linked with the three elements of the COM-B, and thus with the BCW it is possible to target the COM-B factors appropriately when mapping out interventions. Atkins and Michie (35) note that behavior is contextual and materializes within a system of behaviors, which occurs at different levels. Eating is often habitual behavior, which is heavily influenced by the environment (36), i.e., the social and physical opportunities. West and Michie (34) point out that capability and opportunity affect motivation, which then may influence the actual behavior, but that behavioral motivation also competes with alternate behaviors. This means that sometimes it is necessary to decrease another behavioral motivation in order to achieve the targeted behavior (34). Hence, in the context of more plant-based eating, it might be worthwhile to try to decrease the motivation to eat meat, while strengthening the motivation to switch to a more plant-based diets, as well as to try to modify the environment which facilitates habitual (meat) eating behavior.

Graça et al. (37) employed the COM-B in their analysis of consumption orientations and the willingness to transition towards more plant-based diets. They noted that all three components needed improving in order to increase plant-based eating, as did van den Berg et al. (13). Social opportunity was lacking, as social image was seen as a barrier to eat more plant-based meals, and led to abandoning capability and motivation needed for this (37). Consumers who expected eating-related pleasure needed motivation enhancing in relation to better taste and expectations towards plant-based meals (37). Van den Berg et al. (13) found that concerning meat consumption decrease, motivation and opportunity were lacking the most, as the taste of meat and perceived high prices of meat alternatives were seen as barriers.

In a systematic review comprising over one hundred studies, Graça et al. (38) examined reducing meat consumption and following plant-based diets by employing the COM-B model. They noted that while the volume of research on motivational factors regarding more plant-based eating is ample and increasing, studies including opportunity and capability variables are lacking. Our paper focuses on each aspect of the COM-B, and thus allows a broader insight into the factors affecting the consumption of pulses and other plant-based foods. In addition, we analyze the capabilities, opportunities and motivations related to plant protein consumption barriers by taking into account the different sociodemographic factors as well. This helps to identify whether different sociodemographic groups would benefit from varying kinds of actions when advancing more plant-based food consumption.

3. Materials and methods

3.1. Participants and data collection

The consumer survey was part of the Leg4Life (Legumes for sustainable food system and healthy life) research project funded by the Strategic Research Council at the Academy of Finland. The survey was conducted in Finnish and the aim was to collect data on how consumers perceive pulses and PBMAs, their current and future use as well as barriers and enablers related to pulse consumption. The survey data was collected online in September–October 2020 by a consumer and market research company Makery Oy via their existing consumer panel in Finland. The sample ($n = 1,000$) consisted of 18–75 year-old women and men, and was stratified by gender, age group, education level and residential area. Comparison of the participants' sociodemographic characteristics with the Finnish national statistics indicated that the sample represented the Finnish adult population well (for details, see Table 1). The participants did not receive monetary compensation for their contribution, but earned points which can be used to buy goods from the panel's web shop or be donated to charity.

3.1.1. Ethical issues

Prior to data collection, the survey and its protocol were reviewed by the University of Helsinki Ethical Review Board in Humanities and Social and Behavioral Sciences (Statement 40/2020). The respondents were provided detailed information on the study beforehand and they gave their informed consent electronically.

3.2. Measures

The sociodemographic factors examined included gender, age, residential region, urban–rural residency, education, and perceived financial situation. The response options for gender were woman, man and other, but none of the participants chose the last option. Age was recoded into three age groups (18–34, 35–54, and 55–75 years). Participants' place of residence was recoded into four geographical regional categories: Helsinki and Uusimaa region, Southern Finland, Western Finland, and Eastern and Northern Finland. Despite being geographically part of Southern Finland, Helsinki and Uusimaa region was separated into its own category, as Helsinki is the capital of Finland and around 30% of the Finnish population resides in Helsinki and Uusimaa region. Participants' place of residence was also categorized into urban or rural region as defined by Statistic Finland (39). Education was recoded into three classes: elementary, secondary and tertiary education, in which all higher education levels (bachelor, master and post-graduate) were combined into tertiary education. The participants were asked to estimate their own financial situation on a 5-point scale: I get by excellently, I get by quite well, I get by when I shop frugally, I sometimes need to compromise and I need to compromise almost all the time. The first two response options were recoded into a combined category "no financial strain" and the last two options into "financial strain" category, thus resulting in a three-category perceived financial situation variable.

Current pulse and PBMA consumption were studied with the question "How often do you consume the following foods?" with choices for (a) beans, lentils and peas and (b) PBMAs (examples with familiar Finnish product names given in brackets). The response options were never, less than once a month, 1–3 times a month, once a week, 2–4 times a week, 5–6 times a week and daily. These response options were recoded into a dichotomous scale as follows: 1 = never or less than once a month and 0 = more often than once a month for pulse consumption and 1 = never and 0 = at least sometimes for PBMA consumption. This difference in recoding was due to the different share of non-consumers: 46% of the participants reported never consuming PBMAs, while the respective proportion was 8% for pulses.

Future pulse and PBMA consumption were investigated with the question "How do you believe your consumption of the following foods will change in the near future?" (in this paper, we refer to this as future consumption) with choices for (a) beans, lentils and peas and (b) PBMAs (examples with familiar product names given in brackets). The response options (decreases, stays the same, increases and do not know) were recoded into the following dichotomous scale: 1 = increases and 0 = other.

The participants were also asked to evaluate to which extent ten different factors limit their use of pulses and pulse-based products (the two food item types were combined in the same original variable). These factors (later: barriers, see Table 1) were measured on a 5-point Likert scale (1 = does not limit at all – 5 = limits significantly) with "do not know" as an additional response option. The measured barriers were recoded into dichotomous variables as well. Responses with values 1–3 and "do not know" were recoded into "0 = not a barrier" and responses with values 4–5 were recoded into "1 = barrier."

3.3. Statistical analyses

The relationships between current and future consumption of pulses and PBMAs, sociodemographic factors and perceived barriers were analyzed with logistic regression using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, United States). The results are reported as odds ratios (ORs) and 95% confidence intervals (CIs). The threshold for statistical significance was set at $p < 0.05$.

TABLE 1 Descriptive characteristics of the participants, $n = 1{,}000$.

	N	%	Comparison with Finnish population, %*
Gender			
Men	500	50	50.2
Women	500	50	49.8
Age group			
18–34 years	293	29.3	28.3
35–54 years	352	35.2	34.4
55–75 years	355	35.5	37.3
Residential region			(Continental Finland)
Helsinki and Uusimaa region	311	31.1	31.5
Southern Finland (excluding Helsinki and Uusimaa)	200	20.0	20.9
Western Finland	259	25.9	24.8
Eastern and Northern Finland	230	23.0	22.8
Urban–rural residence			
Rural area	214	21.4	
Urban area	786	78.6	
Education level			(20-74-year-olds)
Tertiary	358	35.8	36.7
Secondary	509	50.9	46.1
Elementary	133	13.3	17.2
Perceived financial situation			
No financial strain	442	44.2	
Ok when frugal	375	37.5	
Financial strain	183	18.3	
Current consumption of pulses			
Never	78	7.8	
Less than once a month	215	21.5	
1–3 times a month	284	28.4	
Once a week	192	19.2	
2–4 times a week	182	18.2	
5–6 times a week	34	3.4	
Daily	15	1.5	
Current consumption of PBMAs**			
Never	455	45.5	
Less than once a month	255	25.5	
1–3 times a month	130	13.0	
Once a week	75	7.5	
2–4 times a week	66	6.6	
5–6 times a week	12	1.2	
Daily	7	0.7	
Future consumption of pulses			
Increases	260	26.0	

(Continued)

TABLE 1 (Continued)

	N	%	Comparison with Finnish population, %*
Stays the same/decreases/do not know	740	74.0	
Future consumption of PBMAs			
Increases	195	19.5	
Stays the same/decreases/do not know	805	80.5	
Perceived barriers			
Products are not familiar	440	44.0	
Expensive price	437	43.7	
Do not like the taste	411	41.1	
Unpleasant mouthfeel	337	33.7	
Do not know how to prepare [pulses]	311	31.1	
Family does not want to eat [pulses]	304	30.4	
Narrow product selection	237	23.7	
Do not suit me (e.g., cause stomach problems)	224	22.4	
Preparing [pulses] is tedious	218	21.8	
Hard to find in a store	202	20.2	

*Source: Statistics Finland (2021) and **Plant-based meat alternatives.

Four binary logistic regression models were conducted with sociodemographic and dichotomous barrier variables predicting the odds of (1) using pulses less than once a month or never (29% of participants), (2) never using PBMAs (46%), (3) increased future pulse use (26%), and (4) increased future PBMA use (20%). All predictors were entered simultaneously into the models (see Appendix Table A.1 for logistic regressions testing bivariate associations between each predictor and outcome).

The reference category for each sociodemographic predictor was chosen based on prior studies' results on who are the most likely users of pulses and/or (other) plant proteins. The chosen reference categories were: female, youngest age group of 18–34 years, Helsinki and Uusimaa region (large and medium-sized, urban cities), tertiary education and no financial strain. Reference category for the perceived barriers was "no barrier."

To ensure the suitability of including all sociodemographic and barrier variables as predictors into the same model, Spearman correlation tests were carried out beforehand. All correlations were below 0.5 suggesting no substantial multicollinearity between the predictors.

Ten binary logistic regression models were then performed with sociodemographic factors predicting the odds of each barrier. Again, all predictors were entered simultaneously into the models (see Appendix Tables B.2A,B for logistic regressions testing bivariate associations between each predictor and outcome).

Finally, the number of reported barriers and their association with sociodemographic factors was tested with multinomial logistic regression. The odds of reporting "zero barriers" or "six or more barriers" (with "one to five barriers" as a reference category) was predicted by gender, age group, education level, perceived income and residential region.

4. Results

4.1. Current pulse and PBMA consumption in relation to sociodemographic factors and perceived barriers

We examined 10 perceived barriers often associated with consuming plant-based foods (Table 1). All barriers had prominence at some level, but the most common barriers related to eating pulses were unfamiliarity (44%), expensive price (44%), and not liking their taste (41%). Barriers limiting pulse consumption the least were finding cooking them tedious (22%) and experiencing them hard to find in a store (20%).

Table 2 (left-hand side) shows that the respondents' current consumption of pulses and PBMAs varied according to their sociodemographic characteristics. Lower than tertiary education and financial strain indicated less likely consumption of pulses and PBMAs. Furthermore, age and gender were related to PBMA consumption: men and respondents over 35 years old had lower odds to consume PBMAs than women and the youngest age group.

Our analysis of the association between pulse and PBMA consumption and perceived barriers showed that unpleasant taste and unfamiliarity with the foods resulted in their less likely consumption (Table 2, left-hand side). In addition, expensive price and the difficulty of finding the products in a store were linked to PBMA consumption: respondents finding expensive price and not being able to find the products in a store to be barriers were more likely to consume PBMA than those who did not perceive these as barriers.

4.2. Future pulse and PBMA consumption in relation to sociodemographic factors and perceived barriers

In future consumption of pulses and PBMAs, the sociodemographic trends were largely similar to those detected above for current consumption (Table 2, right-hand side). Having a lower than tertiary education indicated lower odds for increasing pulse consumption, and financial strain was associated with less likely increase in PBMA use.

Increase in men's pulse consumption was less likely than women's, and the oldest respondents had lower odds of increasing their PBMA consumption than the youngest ones. In addition, respondents living in a rural area had lower odds of increasing their PBMA use.

The perceived barriers associated with future pulse consumption were not liking the taste and experiencing pulse products hard to find in a store. Not liking the taste of pulses was related to lower odds of increasing their use. Conversely, experiencing pulses and pulse-based products hard to find in a store led to higher odds of future increase in pulse consumption.

Experiencing pulses and pulse-based products unsuitable (e.g., unpleasant gut symptoms) was linked to lower odds for

TABLE 2 Estimates from multivariable logistic regression models: sociodemographic factors and perceived barriers predicting current and future consumption of pulses and plant-based meat alternatives (PBMAs), *n* = 1,000.

	Current use of pulses (less than once a month or never)		Current use of PBMAs (never)		Future use of pulses (increases)		Future use of PBMAs (increases)	
	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Gender								
Women	1		1		1		1	
Men	1.08	(0.81–1.45)	1.37*	(1.04–1.80)	0.60**	(0.45–0.81)	0.72	(0.52–1.01)
Age								
18–34 years	1		1		1		1	
35–54 years	0.77	(0.53–1.10)	1.58*	(1.12–2.24)	0.80	(0.55–1.16)	0.78	(0.52–1.15)
55–75 years	0.76	(0.53–1.09)	2.74***	(1.94–3.86)	0.87	(0.61–1.26)	0.46***	(0.30–0.70)
Region								
Helsinki and Uusimaa	1		1		1		1	
Southern Finland	1.13	(0.74–1.72)	1.25	(0.85–1.84)	1.01	(0.67–1.52)	0.97	(0.61–1.54)
Western Finland	1.35	(0.91–1.99)	1.14	(0.79–1.64)	0.65*	(0.43–0.98)	0.80	(0.51–1.25)
Eastern and Northern Finland	1.44	(0.96–2.14)	1.17	(0.80–1.70)	0.99	(0.67–1.48)	0.92	(0.59–1.45)
Urban–rural residence								
Urban area	1		1		1		1	
Rural area	1.15	(0.81–1.64)	1.29	(0.91–1.81)	0.67	(0.45–1.07)	0.60*	(0.37–0.95)
Education level								
Tertiary	1		1		1		1	
Secondary	1.55**	(1.11–2.16)	1.96***	(1.45–2.65)	0.69*	(0.50–0.95)	0.68*	(0.48–0.98)
Elementary	2.19**	(1.37–3.48)	2.51***	(1.60–3.93)	0.46**	(0.27–0.78)	0.77	(0.44–1.35)
Perceived financial situation								
No financial strain	1		1		1		1	
Ok when frugal	1.16	(0.83–1.60)	1.21	(0.89–1.64)	1.18	(0.84–1.64)	0.85	(0.59–1.23)
Financial strain	1.89**	(1.27–2.81)	1.69**	(1.15–2.50)	1.04	(0.68–1.60)	0.59*	(0.36–0.98)
Barriers								
Not familiar								
No barrier	1		1		1		1	
Barrier	1.94***	(1.39–2.69)	1.52**	(1.11–2.08)	0.91	(0.64–1.28)	1.24	(0.85–1.81)
Expensive price								
No barrier	1		1		1		1	
Barrier	0.74	(0.54–1.01)	0.49***	(0.36–0.66)	1.11	(0.80–1.53)	1.22	(0.86–1.75)
Do not like the taste								
No barrier	1		1		1		1	
Barrier	1.97**	(1.33–2.90)	1.73**	(1.18–2.52)	0.50**	(0.32–0.76)	0.57*	(0.36–0.91)
Unpleasant mouthfeel								
No barrier	1		1		1		1	
Barrier	0.84	(0.56–1.25)	1.02	(0.69–1.50)	1.37	(0.89–2.13)	0.91	(0.56–1.47)

(Continued)

TABLE 2 (Continued)

	Current use of pulses (less than once a month or never)		Current use of PBMAs (never)		Future use of pulses (increases)		Future use of PBMAs (increases)	
	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Do not know how to prepare them								
No barrier	1		1		1		1	
Barrier	1.06	(0.73–1.55)	0.96	(0.67–1.37)	1.13	(0.77–1.67)	1.94**	(1.28–2.94)
Family does not want to eat them								
No barrier	1		1		1		1	
Barrier	0.90	(0.63–1.28)	1.02	(0.73–1.43)	1.33	(0.92–1.91)	1.03	(0.69–1.55)
Narrow product selection								
No barrier	1		1		1		1	
Barrier	1.01	(0.68–1.51)	1.13	(0.77–1.65)	1.07	(0.72–1.60)	0.89	(0.57–1.40)
Do not suit me (e.g., cause stomach problems)								
No barrier	1		1		1		1	
Barrier	1.00	(0.69–1.44)	1.15	(0.81–1.63)	0.63	(0.47–1.02)	0.59*	(0.37–0.93)
Preparing them is tedious								
No barrier	1		1		1		1	
Barrier	0.86	(0.57–1.30)	0.92	(0.62–1.37)	0.90	(0.59–1.38)	0.67	(0.41–1.07)
Hard to find in a store								
No barrier	1		1		1		1	
Barrier	0.57*	(0.37–0.88)	0.48***	(0.32–0.72)	1.80**	(1.19–2.71)	2.06**	(1.31–3.24)

***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$.

increasing PBMA use in the future. Respondents perceiving pulses and pulse-based products hard to find in a store and not knowing how to cook them as barriers were more likely to increase their PBMA use.

4.3. Sociodemographic factors predicting perceived barriers

The results of the analysis on sociodemographic factors predicting perceived barriers are presented in Tables 3, 4.

Gender Men had lower odds of finding not being familiar with pulses being a barrier for pulse consumption than women did. Men also found not knowing how to cook pulses or pulses not suiting them to be less of a barrier than these were to women.

Age Compared to the youngest age group, the oldest age group had lower odds of perceiving pulses' expensive price a barrier. The oldest respondents were also less likely to find not liking the taste of pulses to be a barrier than the youngest age group. In addition, the oldest respondents had lower odds of not knowing how to cook pulses and finding cooking pulses to be tedious than the youngest participants.

Education and perceived financial situation Respondents with secondary education had higher odds of experiencing not being familiar with pulses a barrier compared to respondents with tertiary education. Financially strained respondents and respondents getting by when shopping frugally were more likely to find pulse-based products' expensive price a barrier than respondents with no such strain. Being financially strained was also related to experiencing more unfamiliarity with pulse-based products and finding cooking them tedious.

Number of reported barriers Altogether 19.2% reported 0 barriers and 18% reported 6 or more barriers (no table). The results from multinomial logistic regression revealed that financial strain was associated with reporting more barriers. Compared to participants with financial strain, those with no such strain had 1.7-fold odds of reporting 0 barriers (95% CI 1.03–2.90, $p < 0.05$) and 0.6-fold odds of reporting 6 or more barriers (95% CI 0.38–0.96, $p < 0.05$). Other sociodemographic factors were not significantly related to the number of reported barriers.

TABLE 3 Estimates from multivariable logistic regression models: sociodemographic factors predicting perceived barriers ($n = 1{,}000$).

	Not familiar		Expensive price		Do not like the taste		Unpleasant mouthfeel		Do not know how to prepare [pulses]	
	OR	95% CI	OR	95% CI	OR	95% CI	OR.	95% CI	OR	95% CI
Gender										
Women	1		1		1		1		1	
Men	0.72*	(0.56–0.93)	1.03	(0.80–1.34)	0.97	(0.75–1.25)	0.99	(0.76–1.29)	0.70*	(0.53–0.92)
Age										
18–34 years	1		1		1		1		1	
35–54 years	1.08	(0.78–1.49)	0.89	(0.64–1.23)	0.88	(0.64–1.21)	0.95	(0.68–1.33)	0.90	(0.64–1.26)
55–75 years	1.03	(0.75–1.41)	0.71*	(0.51–0.97)	0.66*	(0.48–0.91)	0.88	(0.63–1.23)	0.67*	(0.47–0.94)
Region										
Helsinki and Uusimaa	1		1		1		1		1	
Southern Finland	1.04	(0.72–1.51)	0.83	(0.57–1.20)	0.89	(0.62–1.29)	0.98	(0.66–1.43)	0.74	(0.50–1.11)
Western Finland	1.30	(0.92–1.83)	1.01	(0.71–1.43)	1.03	(0.73–1.44)	1.18	(0.83–1.69)	0.83	(0.58–1.21)
Eastern and Northern Finland	1.37	(0.96–1.94)	1.06	(0.74–1.51)	1.14	(0.80–1.62)	1.29	(0.89–1.87)	1.22	(0.84–1.76)
Urban–rural residence										
Urban area	1		1		1		1		1	
Rural area	0.75	(0.54–1.03)	0.82	(0.59–1.13)	0.95	(0.69–1.31)	0.66*	(0.46–0.93)	1.03	(0.73–1.45)
Education										
Tertiary	1		1		1		1		1	
Secondary	1.37*	(1.03–1.82)	1.22	(0.91–1.62)	0.96	(0.72–1.27)	0.93	(0.69–1.24)	1.09	(0.80–1.47)
Elementary	1.17	(0.77–1.80)	1.17	(0.76–1.80)	0.79	(0.51–1.22)	0.66	(0.42–1.05)	0.87	(0.55–1.39)
Perceived financial situation										
No financial strain	1		1		1		1		1	
Ok when frugal	1.11	(0.83–1.49)	1.62**	(1.22–2.16)	1.09	(0.82–1.46)	1.20	(0.89–1.62)	1.06	(0.78–1.44)
Financial strain	1.57*	(1.09–2.24)	2.76***	(1.92–3.98)	1.29	(0.90–1.85)	1.33	(0.92–1.94)	1.33	(0.91–1.95)

***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$.

5. Discussion

We first discuss the general findings of the study. Thereafter we reflect on the findings by employing the COM-B model in analyzing the perceived barriers to pulse and other PBMA consumption. In addition, we take into account the role of sociodemographic factors in our analysis. Lastly, we consider possible measures for future interventions to increase pulse and PBMA consumption.

5.1. General findings

Our results show that pulses are consumed more often than PBMAs: over 90% of the respondents consumed pulses at least sometimes, while just over half of the respondents consumed PBMAs. In total about one fourth of the respondents thought of increasing their pulse consumption, while roughly one fifth planned to increase their PBMA consumption. The most significant barriers for pulse consumption were unfamiliarity (44%), expensive price (44%), and unpleasant taste (41%) of pulses. These barriers represent rather well how all of the COM-B aspects affect the conditions of plant-based eating.

Male gender and older age was associated with lower current PBMA consumption. In addition, men had less intentions to increase their pulse consumption, and older respondents were not likely to increase their PBMA consumption. Siegrist and Hartmann (40) found that women are more likely consumers of meat alternatives, and Jallinoja et al. (25) that women consume beans more often than men. Graça et al. (38) point out that findings from various studies show that the male gender is often associated with unwillingness and the female gender with willingness to follow

TABLE 4 Estimates from multivariable logistic regression models: sociodemographic factors predicting perceived barriers ($n = 1{,}000$).

	Family does not want to eat [pulses]		Narrow product selection		Do not suit me		Preparing [pulses] is tedious		Hard to find in a store	
	OR	95% CI	OR	95% CI	OR	95% CI	OR.	95% CI	OR	95% CI
Gender										
Women	1		1		1		1		1	
Men	0.78	(0.59–1.02)	1.26	(0.94–1.69)	0.64**	(0.47–0.87)	1.01	(0.75–1.37)	1.09	(0.80–1.49)
Age										
18–34 years	1		1		1		1		1	
35–54 years	1.39	(0.99–1.95)	0.79	(0.55–1.15)	1.31	(0.89–1.91)	0.71	(0.49–1.04)	0.68	(0.46–1.00)
55–75 years	0.72	(0.51–1.03)	0.86	(0.59–1.23)	0.95	(0.65–1.41)	0.63*	(0.43–0.92)	0.73	(0.50–1.07)
Region										
Helsinki and Uusimaa	1		1		1		1		1	
Southern Finland	0.98	(0.65–1.46)	0.76	(0.49–1.18)	1.14	(0.75–1.73)	0.76	(0.49–1.19)	0.68	(0.42–1.09)
Western Finland	1.07	(0.74–1.55)	0.96	(0.65–1.42)	0.79	(0.53–1.20)	0.92	(0.61–1.38)	0.96	(0.63–1.45)
Eastern and Northern Finland	1.29	(0.88–1.88)	1.12	(0.75–1.68)	0.89	(0.58–1.35)	1.05	(0.69–1.58)	1.15	(0.76–1.76)
Urban–rural residence										
Urban area	1		1		1		1		1	
Rural area	1.28	(0.91–1.80)	0.85	(0.58–1.25)	1.16	(0.79–1.68)	0.95	(0.65–1.40)	0.98	(0.66–1.46)
Education										
Tertiary	1		1		1		1		1	
Secondary	1.21	(0.90–1.65)	1.10	(0.79–1.53)	0.89	(0.64–1.24)	0.98	(0.70–1.37)	1.09	(0.77–1.55)
Elementary	0.89	(0.55–1.43)	0.79	(0.47–1.32)	0.82	(0.49–1.36)	0.83	(0.49–1.40)	0.78	(0.45–1.35)
Perceived financial situation										
No financial strain	1		1		1		1		1	
Ok when frugal	0.86	(0.63–1.17)	1.06	(0.76–1.49)	1.43*	(1.02–2.02)	1.06	(0.75–1.49)	0.88	(0.62–1.26)
Financial strain	1.07	(0.73–1.57)	1.45	(0.97–2.18)	1.43	(0.94–2.18)	1.53*	(1.01–2.31)	1.31	(0.85–2.01)

***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$.

plant-based diets, but that results concerning age are mixed. Interestingly in our study, men and older respondents found certain barriers to limit their pulse consumption less than women and the young did, even though the latter are more often profiled to be more interested in plant-based foods.

Earlier research shows that higher education predicts more frequent bean consumption (25), and readiness to accept PBMAs (40, 41). Overall, higher socioeconomic status acts as an enabler to consume plant-based foods (38), and different economic situation may lead to different access to certain consumer goods (42). Our results are in line with this, as lower education level and financial strain were associated with lower pulse and PBMA consumption. Living area was not strongly associated with pulse and PBMA consumption, even though some earlier research has found that living in large or medium-sized cities often indicates a tendency to consume plant-based foods [e.g., (14)].

5.2. Capabilities, opportunities, and motivations limiting the consumption of pulses and pulse-based products

5.2.1. Unfamiliarity and preparation capabilities

Being unfamiliar with pulses and other plant-based foods is a significant barrier for their consumption, as earlier research [e.g., (29)] as well as our results show. Unfamiliarity affects the *psychological capability* to eat these kinds of foods. We discerned that current use of both pulses and PBMA products was likely to be limited due to unfamiliarity. In addition, some sociodemographic groups found unfamiliarity to be more of a barrier than others; most notably women and those with financial strain. We propose that the gender difference may be because some men are not that interested in consuming pulses or PBMAs, and thus do not experience any barriers related to them either. Furthermore, if money is tight, it may feel safer to buy familiar options to get one's money's worth (43, 44). Oude Groeniger et al. (45) argue that consuming healthy food is one mechanism for social distinction in the higher socioeconomic classes, and Bowman (46) points out that lower education level can in some cases be associated with the lack of knowledge of the benefits of more plant-based eating, and that plant-based eating might be seen as something that belongs to those with higher education (and thus often higher socioeconomic status). To summarize, pulse unfamiliarity as a psychological capability affects especially people with lower socioeconomic status and women.

Unfamiliarity is closely related to inability to cook pulses and pulse-based products and finding preparing them to be tedious, which can be classified as both *psychological* (e.g., not knowing how) and *physical* (e.g., not having enough time) *capability*. Nguyen et al. (47) conceptualize cooking skills as a physical capability, and their absence acts as a barrier to alternative protein source consumption. Again, women experienced the inability to cook pulses and pulse-based products to be more of a barrier than men did, which refers to the idea above that men may not be as interested in pulses, and thus have no barriers. However, women are more willing to eat plant-based foods (38) and to try vegetarian recipes (13) than men. Additionally, older respondents had less feelings of inability to cook pulses and pulse-based products, and they also found preparing pulses less tedious than younger respondents. We propose that this is an indication of older respondents being more used to cooking from scratch: convenience and time-saving is especially valued by the younger generation [(12); see also (48)].

5.2.2. Taste and unpleasant gut symptoms

Similarly to our findings, earlier studies have concluded that the unpleasant taste of pulses is a barrier to consuming them (28, 29, 31). Furthermore, doubting the taste of PBMAs prevents their use (35), and liking meat is often a barrier for meat alternative consumption (47). In the context of eating, pleasure is one major motivation to consume certain kinds of foods (43, 49), and good taste is significant for achieving pleasure. Taste can be classified as *automatic motivation*. In our study, the unpleasant taste of pulses was a significant barrier for both current and future consumption of pulses and PBMAs. Older respondents experienced the taste to be less of a barrier than the youngest, but Jallinoja et al. (23) found that young consumers were more likely to eat beans. Thus, we argue that taste of pulses may be perceived differently by different groups of people, depending on, e.g., their generation, social upbringing and taste preferences.

Pulses are often perceived to cause unpleasant gut symptoms: even up to one third of the Western population suffers pulse digestion problems (50). This can act as a barrier for pulse use, as undesired gastrointestinal symptoms may physically limit the capability to consume pulses. Winham and Hutchins (50) found that women were more likely to report gastrointestinal symptoms and sensations, which is in line with our finding that women found pulses causing unpleasant gut symptoms more of a barrier than men did. Earlier research has also concluded that pulses' gastrointestinal unsuitability limits the capability to consume them (14, 29, 31).

5.2.3. Price

Graça et al. (38) discuss the higher price of meat as a potential enabler for increased plant protein consumption. However, there are mixed results on perceived plant protein prices: Vainio et al. (28) discovered that the expensive price of plant protein foods was the most significant barrier for their consumption, while Niva et al. (29) concluded that price was not a barrier. Furthermore, van den Berg et al. (13) found price to both prevent and enable eating PBMAs: the perceived high price of PBMAs was a barrier, but saving money was also seen as a reason to consume less meat and more plant proteins. In our study, pulses *per se* and pulse-based products were lumped together when enquiring about the price, even though their prices often differ significantly. We found that the price of pulses acted as a barrier for respondents struggling financially, thus limiting their *physical opportunity* to consume these products, which possibly indicates that they thought of pulse-based meat alternatives rather than pulses *per se*, as the latter are often quite inexpensive. Lower prices of pulse-based products would create more opportunities for consumers to increase their pulse intake (30). We also found that those already consuming PBMAs perceived their price to be more of a barrier than non-consumers. We propose two explanations for this. First, there may be a group of non-consumers for whom the barrier is not the price of the products, but other factors. Secondly, there may be consumer groups, such as young students, who would like to consume more PBMAs, but find their high price to limit their consumption opportunities.

Age can also be a factor affecting the perception of price: we found that the oldest respondents had less of a price barrier than the youngest, which suggests that they may be financially better off or that they may have thought of different pulse products, i.e., pulses *per se* versus processed products. Our notion of older respondents not consuming and not intending to consume PBMAs supports this interpretation. In addition, perceptions of plant-based foods and their price may vary culturally: the Spanish found plant-based eating more affordable than the Danish (51). In Spain, the traditional Mediterranean diet includes affordable dried and fresh pulses (52), while Northern Europeans often like to emphasize the convenience of food products (53), and thus may prefer more expensive, ready-to-use pulse products.

5.2.4. Store and family environment

Another physical opportunity affecting pulse and PBMA consumption was having difficulties in locating these products in a store. Earlier research has noted that more prominent positioning of healthy foods (such as pulses) in grocery stores is related to healthier food choices (54) and that alternative protein foods are often placed separately from meat equivalents (55). Thus, with better placement of plant protein foods, grocery stores could advance their consumption. Curiously, respondents already consuming pulses and PBMAs and intending to increase their consumption found not being able to find these products in a store to be more of a barrier than non-consumers. Again, there might be a group of non-consumers who have not even tried to find pulses in a store, which is why it is not a barrier. Other explanations can also be offered. The first is that some stores may not carry a large selection of pulse products, which is why they are hard to find (however, this did not seem to be an issue when examining "narrow product selection" barrier). The second is that some products might be stocked low and often sold out, resulting in not finding them. The third is that not all stores have clearly organised sections where all pulse products are conveniently on display, resulting in shoppers needing to navigate through multiple sections before finding the right product (or not finding it at all), which also calls for their better positioning.

Social environment can act either as barrier or enabler for decreasing meat consumption and/or increasing the portion of plant-based foods (38). We only examined family as the social environment (i.e., social opportunity) relating to pulse consumption barriers, and even though 30% of respondents perceived this as a barrier, it was not statistically significant in our study. Van den Berg et al. (13) had similar results, as they noted that people were mostly able to decide themselves which foods to consume regardless of the social environment. Other barriers which were not statistically significant in relation to current and future pulse and PBMA consumption in our study were mouthfeel (relating to the pleasure aspect of motivation) and narrow selection of pulse products (physical opportunity).

5.2.5. Intervention measure suggestions

Habits are often unconscious and triggered by the environment, and intentions do not necessarily translate into actual behavior (36). One behavior may be a barrier to another (34), and automatic motivation may override reflective motivation (35). Thus, to conclude our discussion, we propose some possible future intervention measures within the COM-B model to increase the consumption of pulses and PBMAs.

As the present results demonstrate, lower education level and financial struggle are associated with consuming pulses and PBMAs more infrequently. One commonly proposed solution is to increase the proportion of plant-based meals in workplace canteens, but the problem is that people with lower socioeconomic status often do not have access to these places (56) and consume homemade or bought food. However, in Finland, children are provided with free daycare and school lunches (57), and thus one way to increase plant-based eating could start from these public food services. There have been prior attempts to increase the amount of vegetarian food in schools that have led to mixed results: on the other hand, food waste increased and participation at lunch decreased, but some vegetarian dishes gained popularity (58). To further increase plant-based food consumption at school lunches, the physical opportunities need to be taken into account. One way to enhance this is to place plant-based dishes first on the serving line. However, for plant-based dishes to be more readily accepted, the social opportunities need to be present as well. At present, meat dishes are seen as more "normal," as the need to specifically distinguish vegetarian food days in schools demonstrates: there is no talk of "meat food days." Thus, plant-based foods should be normalized and not differentiate them from meat dishes conspicuously. In addition, home economics classes at schools can help to normalize plant-based foods and to achieve capabilities to cook tasty and nutritious plant-based meals. All these measures would also make pulses more familiar, which is an enabler for their consumption (10).

The present findings suggest that the food industry and retail trade can enhance the motivation and physical opportunities to eat plant protein foods. We noted that unpleasant taste was one significant barrier for consuming pulses and PBMAs. Improving taste qualities of plant protein foods and maybe offering appealing convenience meals without meat could increase the motivation to consume them. Furthermore, perceived high prices hindered plant protein food consumption. To steer consumers towards plant protein foods, changes in taxing meat and plant protein sources could make plant foods more appealing and financially more available to all. Finally, grocery store settings could be modified to help consumers find meat alternatives without having to make a significant effort. For example, Piernas et al. (59) found that by placing alternative proteins in the meat aisle, their sales increased. Thus, by placing plant proteins next to meat products would make it easier for consumers to find and buy meatless alternatives.

5.3. Strengths and limitations

One strength of the study lies in using large and recent survey data including respondents who relatively well represent the general Finnish adult population in terms of gender, age, living area and education level. The most notable strength is that we analyzed the role of sociodemographic factors simultaneously with the consumption of pulses and PBMAs and the barriers related to them; a topic that is of importance if a transition towards more plant-based food consumption is to be achieved.

One limitation to consider is that pulses as raw ingredients and pulses as processed products were lumped together in the survey when enquiring about the factors perceived as barriers to their use. This is somewhat problematic, because pulses *per se* and processed pulse products often differ in price, preparation technique and taste, amongst other things. Furthermore, there is no certainty that the self-reported pulse consumption reflects actual consumption, or that intentions to increase consumption will actually be realized.

6. Conclusion

Our results show that the level of engagement among Finnish adults in the consumption of plant-based protein foods is currently not very high, and the intentions to increase their consumption are rather low as well. As our study demonstrates, sociodemographic factors have a role in pulse and PBMA consumption, most notably gender, age, education and perceived financial situation. Age and gender were also prominent factors in relation to perceived barriers to pulse and pulse-based product consumption. Our research also shows that the COM-B model is relevant when examining pulse and PBMA consumption. First, eating plant-based foods requires motivation to do so, and the major motivational barrier in our study was the unpleasant taste. Second, there needs to be suitable opportunities to further engage consumers in pulse and other plant-based protein consumption, e.g., in terms of affordability and store settings. Third, consumers need sufficient capabilities to be able to prepare enticing pulse- or other plant-based dishes, but unfamiliarity with and uncertainty in preparing pulses and PBMAs are barriers to their consumption. Thus, offering easy to use, tasty and affordable pulse and other plant protein-based dishes and products can pave the way towards more environmentally sustainable food consumption.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of Helsinki Ethical Review Board in Humanities and Social and Behavioral Sciences. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their consent electronically.

Author contributions

SK, MN, A-MP, KK, TM, and HK contributed to conception and design of the study. HK, KK, A-MP, and TM were responsible for data collection. SK performed statistical analyses, wrote the first draft of the manuscript, and had primary responsibility for the final content of the manuscript. HK collaborated in conducting the statistical analyses. HK, MN, A-MP, KK, and TM commented and critically revised the manuscript. All authors contributed to the article and approved the submitted version.

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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

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2023.1186165/full#supplementary-material

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Evaluation of public submissions to the USDA for labeling of cell-cultured meat in the United States

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With the rapid advancement of cell-cultured meat processing technologies and regulations, commercialization of cell-cultured meat to market shelves requires the implementation of labeling that informs and protects consumers while ensuring economic competitiveness. In November 2022, the United States Food and Drug Administration (FDA) completed its first pre-market consultation of cell-cultured meat and did not question the safety of these products for human consumption. As of June 2023, commercialization of cell-cultured meat products has become a reality in the United States. To derive potential label terms and gain insight into how different stakeholders refer to these novel products, we analyzed 1,151 comments submitted to the 2021 U.S. Department of Agriculture's Food Safety and Inspection Services (USDA-FSIS) call on the labeling of cell-cultured meat and poultry. Our first aim was to systematically assess the nature of comments with regards to their length, cited references, and supplemental materials. In addition, we aimed to identify the most used terms to refer to these products through text analysis. We also asked how these analyses would vary by affiliation category and economic interest. Using the listed organizations for each comment, we first determined financial ties: 77 (7%) comments came from those with an economic interest, 12 (1%) of the comments did not have an identifiable economic interest, while for the remaining 1,062 (92%) comments economic interest could not be determined. We then grouped comments into affiliation categories. Cell-cultured meat companies and animal welfare non-profits had the highest median word count, whereas comments from the unknown affiliation category had the lowest. We found across all comments the predominantly mentioned potential label terms, in descending order, to be *cultured meat, lab-grown meat, cultivated meat, cell-cultured meat, clean meat, and cell-based meat*. While all label terms were discussed throughout overall submissions, percentages of comments mentioning each term differed between affiliation categories. Our findings suggest differences in how affiliation categories are discussing cell-cultured meat products for the US market. As a next step, the perception and acceptance of these terms must be evaluated to identify the optimal label term regarding the information and protection provided to consumers while ensuring economic competitiveness.

KEYWORDS

cellular agriculture, food policy, labeling, meat, public comment analysis, text analysis

1. Introduction

Alternative meat innovation has advanced with increased awareness of the traditional meat farming industry's impact on global sustainability and food security. US Americans are among the top five consumers of beef, veal, pork, and poultry meat (1). The impact of traditional meat production on greenhouse gas (GHG) emissions and water use poses global sustainability issues (2). Beef farming in particular represents almost half of GHG emission associated with agriculture in the United States (3). While research has prioritized decreasing environmental impacts of traditional meat production, several studies report that a majority of consumers are unaware of negative implications of meat production and consumption (4–6). Currently, few consumers choose meat alternatives to replace traditionally farmed meat due to their dissimilarity in terms of flavor and texture (7). Food insecurity has increased globally since the COVID-19 pandemic (8). The rising world population also imparts further issues toward adequate meat production; global food production must increase by 70% by 2050 to meet demands (9). The disruption of the economy from the pandemic paired with the influx of the world population creates an obstacle for consumers to purchase and consume protein-rich foods with a lower environmental impact (10).

Cell-cultured meat[1] has emerged as an alternative and parallel production to traditional meat due to the potential positive impact on global sustainability, paired with a sensory experience that mimics that of traditionally farmed meat (11). However, it remains unclear how able the cell-cultured meat industry will be to successfully manufacture products that at the same time meet these goals. (12). As production processes are still being optimized, little is known of the taste, nutrition, safety, and environmental impact of large-scale production of these products (13, 14). Further, differences in acceptance of cell-cultured meat hinders broad public appeal (15, 16). Cell-cultured meat is produced through a process starting by (1) identifying and isolating target cell and tissue, (2) selecting and expressing target cells, (3) culturing of cells, (4) collecting of cell biomass, and (5) processing into a meat product (17). While this process has the potential to create meat products while using less water, consumer perception varies, which may be attributed to differences in consumer attitudes including food technology neophobia (13).

In the United States, the FDA approved cell-cultured meat production in November 2022 followed by the USDA's approval for commercialization in June 2023 (17, 18). While the regulatory barriers for production and sales of cell-cultured meats have been lowered, there is a gap in determining how these products should be labeled. In 2021, the United States Department of Agriculture's Food Safety and Inspection Services (USDA-FSIS) published an advanced notice of proposed rulemaking (ANPR), open to public submission. They sought public input regarding the labeling of cell-cultured meat and poultry (19). The purpose of the ANPR is to establish the intent of a new rule or regulation and allow for public comment *via* an open response forum to gain insights into public opinion to facilitate rule development. There are no requirements regarding who is able to submit a comment. According to the Federal Register, an "*Advance Notice is a formal invitation to participate in shaping the proposed rule and starts the notice-and-comment process in motion*" (20).

Specifically, the ANPR gathered public comments on cell-cultured meat with 14 questions provided by FSIS (see Supplementary Table S1). These questions prompted responses on potential labeling strategies, the impact of the label terms on the meat market, and how these labels would differentiate cell-cultured meat products from traditionally farmed meats (19). To understand the views of the public, we analyzed ANPR comments with text analysis tools to gain insight into how proposed labels differ between affiliation categories of comment submitters.

Regulation and identification of cell-cultured meat within the standards of identity of meat must be implemented for consumers to make informed purchase decisions. There are two sections within the Code of Federal Regulations in which cell-cultured meat must be addressed, namely, how meat is defined and how meat is labeled. The Federal Meat Inspection Act, found in 9 CFR301.2, legally defines foods including meat, meat byproduct, and meat food product (21). While cell-cultured meat does not abide by the definitions for meat or meat byproduct as it is not "part of the muscle of cattle" or "any part capable of use as human food" (21), it certainly would fit into the definition of a meat food product, "any article capable of use as human food which is made wholly or in part from any meat or other portion of the carcass…" (21). This legal ambiguity of what differentiates traditional meat from cell-cultured meats is part of the challenge of how to label these products, not only in the United States but around the world (22).

Labeling definitions and characteristics of meat, meat byproducts, and meat food products are regulated as described in 9 CFR 317.2 (23). There it is stated that for any product with no common or usual name, a descriptive designation used as a product name must clearly and completely identify the product. Further, meat preparation processes (e.g., smoking, salting) must be identified on the label and industry relevant terms (e.g., "picnic," "cala") shall not be used as the product name unless paired with descriptive terms (e.g., flavorings, marinades), or with a list of ingredients, to ensure transparency (23). With cell-cultured meat companies, such as Upside Foods and Good Meat, recently receiving regulatory clearance for production and sales, stakeholders must consider these parameters when establishing labeling strategies. Such strategies could include omission of the word 'meat' all together and/or use of another term, such as 'protein'.

With commercialization of cell-cultured meat in the United States, meat industry stakeholders vary in their support for these new products. Due to the potential for cell-cultured meat to take over a percentage of the market share within the traditional meat industry, established traditional meat farmers may experience negative impacts in terms of food security and profits (24). On the other hand, success in the cell-cultured meat industry could be dependent on cell lines obtained from healthy cattle raised by traditional meat farmers, therefore transparency and communication strategies must be enforced to ensure fairness and equity between these two groups. Here, we seek to identify differences in proposed labeling strategies submitted to the ANPR as a function of meat industry stakeholder groups and affiliations (e.g., cell-cultured meat vs. traditional meat companies).

1 In this study, we will align with the USDA-FSIS referencing food products produced by cell-culture as "cell-cultured meat."

An interesting case in this effort represents Tyson Foods, a top investor in cell-cultured meat as well as an established leader in the traditional meat farming industry. Tyson has invested in companies developing cell-cultured meat such as Upside Foods, Memphis Meats, and Future Meat Technologies (25–27). As such, Tyson Foods' comments on how cell-cultured meat should be commercialized and labeled presents an opportunity to analyze how potential opposing viewpoints could be resolved. For these reasons, we chose to analyze Tyson Foods' submission separately.

We outlined three main objectives for this study. First, we aimed to determine the extent and disclosure of comments as they relate to economic interests and affiliation. We hypothesized that those with a stated economic interest will have a higher percentage of submissions compared to those without identified financial ties. Here, we further defined an economic interest as those who experience impact to their economic status with the commercialization of cell-cultured meat. Further, we also hypothesized that different affiliate categories will differ in their submissions with regards to length and extent of providing scientific evidence and supplemental materials, with cell-cultured meat companies hypothesized to provide more external reference citations than traditional meat companies.

For the second objective, to identify the predominant labeling terms used for cell-cultured meat across the different affiliation categories, we hypothesized that the cell-cultured meat industry and traditional meat farming industry will refer to these novel products in their submission using different label terms. Further, we evaluated the diversity of label term constructs (i.e., hyphenated, preceding, and root terms). For example, label term constructs could be "cell-cultured meat," "man-made protein," which were similarly analyzed to create a comprehensive list.

Last, the submission received by Tyson Foods was treated as a special case due to the economic interests of this company in both traditional meat farming and cell-cultured meats. Analyzing this submission as described above, we hypothesize that the Tyson Foods submission will mention label terms similar to the predominant labels mentioned by the traditional meat farming affiliation group due to their longer history in the traditional meat industry.

Outcomes from a systematic and scientific evaluation of the comments submitted to the USDA-FSIS ANPR will provide an overview of submission extent, disclosure, and label term use for industry and regulatory professionals to gain insight on current terminology regarding cell-cultured meat in various sectors. Results from our systematic analysis could form the basis of future consumer insights research, to assess perception and acceptance of different labels for these novel food products. Our analytical method, pairing automated text analysis tools with manual evaluation, allows for a comprehensive assessment of terms used to discuss these products.

2. Materials and methods

2.1. Dataset

On 3rd September 2021, the USDA-FSIS started collecting open responses *via* an ANPR regarding "labeling of meat or poultry products comprised of or containing cultured animal cells." The proposed rule contained 14 items (see Supplementary Table S1) for public comments including how products should be labeled, how label terms impact consumer choice, standards of identity, and the meat market. The submission period was initially opened until 2nd November 2021, but extended until 2nd December 2021. A total of 1,207 comments were received during this timeline, of which 1,180 were available for download. The remaining 27 comments were inaccessible due to the USDA-FSIS quality standards; no further information was provided. The data was accessed for analysis on 12th September 2022 *via* the USDA-FSIS website and exported to Microsoft Excel. While most comments were viewable in the Excel file, some comments were extracted by downloading pdf and/or Microsoft Word files that were available in the Excel file as downloadable attachments. All data analyzed in this study were retrieved from Regulations.gov, the United States Federal government website document repositor.[2]

2.2. Data analysis

A comprehensive outline of our data analysis procedures is summarized in Supplementary Figure S1. Upon manual inspection of all submissions, those that were duplicated ($n = 18$), unrelated ($n = 2$), blank response ($n = 2$), or requesting an extension for the submission period ($n = 5$) were omitted from further analysis. One submitted Excel file, containing 6,028 identical entries, was also omitted from analysis. Supplemental submission materials were not analyzed as part of the median word count analysis. In addition, citations, welcoming introductions, repeated USDA-FSIS proposed questions, and closing remarks were manually removed to standardize submission comments to only contain information regarding labeling of cell-cultured meat. After cleaning, 1,152 comments, including the Tyson Foods submission, were used for analysis. Over 99% of submissions (1,143 out of 1,152) were made by individuals or entities residing in the United States, based on the stated location for each comment.

Several inferences were made for our analysis. Economic interest of submissions was evaluated to determine the extent and disclosure of comments relative to their economic relation to the cell-cultured meat industry. Economic interest was determined by manual web and/or social media searches and established using one or more of the following parameters:

1) Direct connections to the cell-cultured meat industry, e.g., cell-cultured meat companies.
2) Cell-cultured meat production and sales may directly affect their market share in the meat industry, e.g., traditional meat farmers.
3) Economic interest was outwardly stated in comment.
4) Non-profit organizations who represent the interests of companies satisfying points 1 or 2, due to dependency on each other for economic success.
5) Research organizations who receive funding related to the cell-cultured meat industry.
6) Investments in companies satisfying 1 or 2.

Affiliation categorization was determined by manually researching each organization and sorting submissions into affiliation categories

2 https://www.regulations.gov/docket/FSIS-2020-0036/comments

that were identified *via* discussions by the author team (see Supplementary Table S2): cell-cultured meat companies, traditional meat farmers, research organizations, farmer advocacy groups, federal, state, and government agencies, animal welfare non-profits, other, and no affiliation. Cell-cultured meat companies included companies that produce cell-cultured meat. Traditional meat farmers included companies that produce traditionally farmed meat. Research organizations included organizations that perform research related to cell-cultured meat, agricultural sustainability, human nutrition, food safety, and genetically modified foods. Farmer advocacy groups included organizations that advocate for traditional meat farming practices. Federal, state, and government agencies included responses from those agencies and representatives of those agencies. Animal welfare non-profits included organizations that advocate for ethical farming practices. Other was recorded when there was an affiliation listed but it did not fit into the previously listed categories. Unknown affiliation included those who commented that did not identify an affiliation. This included 131 submissions made from differing individual submitters that started "As an Arkansas farmer …" Due to lack of disclosure of an organization, these submissions were categorized in the 'unknown' category.

Once submissions were cleaned and categorized, a combination of manual and automated analyses in R, NVivo, and Microsoft Excel was conducted across all comment submissions and per affiliation category. The number of scientific references and supplemental information was manually quantified and recorded for each submission. This was performed by examining footnotes, bibliographies, and in-text citations. The percent reported was calculated by counting the number of comments containing cited references for each affiliation category. Mean citation count was quantified by reporting the total number of references for each submission and calculating the mean for each category. Supplemental information included slide presentations, attached research articles, and summary booklets. Supplemental information counts were quantified from manually counting and calculating total submissions that attached supplemental information counts. Analysis was performed in R (V.4.2.1), using the RStudio environment (V.2022.7.2.576, Boston, MA) with the additional packages ggplot (28), dplyr (29), tidytext (30), and ggpubr (31). We used dplyr and tidytext to evaluate the word count for each group by affiliation and economic interest reported as median and range word count. Comments were analyzed directly in RStudio, as they were within the cell character limit of Excel (32,767 characters). However, two comments (Good Food Institute, Harvard Animal Law & Policy Clinic/Harvard Food Law and Policy Clinic), which had content larger than this were analyzed manually *via* Microsoft Word.

Then each submission was analyzed for commonly mentioned label terms (e.g., cell-cultured, cultivated, clean, etc.) – this was done in step-wise manner using NVivo (version 12, QSR International, Burlington, MA): First, common words and phrases were identified surrounding the most common word mentioned 'meat'. We used the 'word tree' function to identify the hyphenated and preceding terms to 'meat'. Then each term was evaluated by 'text search queries' to identify the most common label term constructs used overall. We further performed a forwards and backwards analysis of preceding and hyphenated terms by word trees to evaluate root terms used to discuss these products. An overview of label term constructs was recorded in Excel (see Supplementary Table S3).

Using the most common label terms identified in overall comments, the Microsoft Excel advanced search was used to obtain counts of comments mentioning each term. All text search analysis was performed by searching for the full label term construct. The results were recorded in Excel for data visualization in R. We analyzed the percentage of submissions mentioning each label term overall and by affiliation category. To compare between affiliation categories, which differed in number of submissions, we report percentages of submissions within each affiliation group mentioning each label term. This was calculated by quantifying the number of submissions that mentioned each label within each affiliation category, divided by the total submission count for each category, and multiplied by 100. The same analysis was completed for the Tyson Foods submission. However, for Tyson Foods we did not calculate a percentage since $n = 1$ in this case.

3. Results

3.1. Economic ties and affiliation do not predict total submission count or word count

Our first research question addressed the extent and disclosure of comments related to economic interest. Extent is defined as the length and content of the submission which we evaluated using word count, number of references, and supplemental information. When there was an organizational tie which could identify economic interest, we used the term 'disclosure' to identify this group. We defined economic interest as those who have a financial tie to the cell-cultured meat or traditional meat farming industry (see Materials & Methods section). We hypothesized that those with economic interest will have a higher percentage of submissions both in number as well as length (i.e., median word count) in comparison to those without an identified economic interest. However, our analysis shows (Supplementary Table S4) that only 77 (6.7%) comments were submitted by an entity with an identifiable economic interest, 12 (1.0%) comments were entered by those without an identified economic interest, and the vast majority, 1,062 comments (92.3%) were submitted where the economic interest could not be identified (e.g., anonymous submission or submission as a private citizen).

Table 1 provides an overview of the origin and characterization of submissions by affiliation category. The parameters of comment composition (e.g., word count, number of references, and extent of supplemental information) was hypothesized to predict economic interest. We found that affiliation category did not impact submission extent or disclosure. Percentages of submissions by affiliation were calculated for each category and reported in Table 1. The majority of comments came from those with unknown affiliation ($n = 1{,}062$; 92.3% of submissions) which also had the lowest median word count of 68, or roughly one paragraph (Table 1). Cell-cultured meat companies made up 1.2% of submissions and had the second largest median word count of 2048, or roughly 2.5 letter sized pages single spaced (Table 1). The lowest number of submissions came from traditional meat farmers with 2 submissions (0.2%), neither of which included references or supplemental information, and had a median word count of 1,208. The greatest number of comments from those with a listed affiliation came from farmer advocacy groups, who

TABLE 1 Presence of affiliations, citation of scientific evidence, supplemental information, and median word count.

Affiliation category	% of Total (*n*)	% Citing references (*n*)	Mean citation count	Median word count (Range)	Comments with supplemental information
Cell-cultured meat companies	1.2 (14)	64.3 (9)	8.1	2048 (283–4,614)	2
Traditional meat farmers	0.2 (2)	0 (0)	0	1,208 (848–1,567)	0
Research organizations	1.0 (11)	90.9 (10)	7.8	1,337 (359–5,990)	1
Farmer advocacy groups	3.2 (37)	13.5 (5)	1.1	756 (202–4,771)	1
Animal welfare non-profits	0.3 (4)	75.0 (3)	18.8	2,379 (626–3,291)	1
Government agencies	1.0 (11)	9.1 (1)	0.8	642 (323–1969)	0
Other	0.9 (10)	30 (3)	15.5	742 (66–8,731)	1
Unknown affiliation	92.3 (1062)	0.5 (5)	0.1	68 (1–4,609)	6

submitted 37 comments (3.2%), with a median word count of 756 (Table 1). All other affiliations had comparable submission numbers ranging from 2 to 14 submissions (Table 1). The highest median word count of 2,379 were made by animal welfare non-profits who also had the highest mean citation count (Table 1).

Percent citing references and mean citation counts differed greatly both by economic interest and affiliation: we found that those without identified economic interests ($N = 12$) had the highest mean citation count ($M = 19.2$), highest percent citing references (32%), and highest median word count (Mdn = 1766) (Table 1). The affiliation category with the highest percent of cited references included research organizations – of the 11 submissions in this group 90% cited references in their comments. The inclusion of supplemental material, as previously defined as additionally submitted materials together with the comment, did not differ by economic interest or affiliation categories (Supplementary Tables S1, S3). However, the comments for which no affiliation could be assigned showed the highest number of comments with supplemental information (Table 1). Upon further manual inspection these included PowerPoint presentations, figures, and peer-reviewed scientific manuscripts.

3.2. The same top 6 label terms were identified across all comments, however, label term mentions differ greatly across affiliation categories

Our second research question assessed how different commenters referred to these novel food products in their submissions, as an indirect way of identifying potential labels for these products. Using NVivo to identify the top label terms, we found the most widely used overall, in descending order of percent of comments mentioned, to be *cultured meat* (29.8%), *lab-grown meat* (13.6%), *cultivated meat* (8.2%), *cell-cultured meat* (5.6%), *clean meat* (5.2%), and *cell-based meat* (3%) (Figure 1A). These top 6 terms accounted for 2/3 of all comments.

Due to the ambiguity in application of the current standards of identity for meat, potential labels could also omit the root term 'meat'. Therefore, an additional analysis was carried out to identify root terms other than 'meat' or no root term at all, across all submissions and by affiliation category. Upon analyzing the top 6 hyphenated and preceding terms regardless of root term (i.e., searching without the root term 'meat'), a similar rank order was found, except for *cell-based* and *clean*. Compared to analysis including the 'meat' root term, mentions of *cell-based* and *clean* switched rank order, with *cell-based* (9%) having higher mentions than *clean* (8%) (Figure 1B). The analysis without the root term *meat* also identified the label *lab-cultured* as a top label term (12%) (Figure 1B), as it was referenced by the unknown and government agencies affiliation groups in conjunction with the root term 'protein'.

Using the top 6 terms in conjunction with the root term 'meat' identified in our analysis, we then focused on our second research question of how percentages of label terms mentioned in comments might differ across affiliation categories (Figure 2). To better understand the use of the hyphenated and preceding label terms, we further analyzed them without the root term 'meat' in Supplementary Figure S2. It was observed that overall trends of label mentions for each affiliation category were similar when analyzed with and without the root term 'meat' (Figure 2, Supplementary Figure S2). Among the mentions of the top 6 terms, differences in percentages are apparent between affiliation categories: While cell-cultured meat companies predominantly used the term *cultivated meat* (64.3%), all other terms were mentioned between 25–50%, except *cell-based meat* which was mentioned in less than 10% of submissions (Figure 2A). On the other hand, traditional meat farmers primarily used the terms *cell-cultured meat* and *cell-based meat* 100% of the time (Figure 2B). However, it is important to note that only 2 submissions made up the traditional meat farmers affiliation category. Interestingly, research

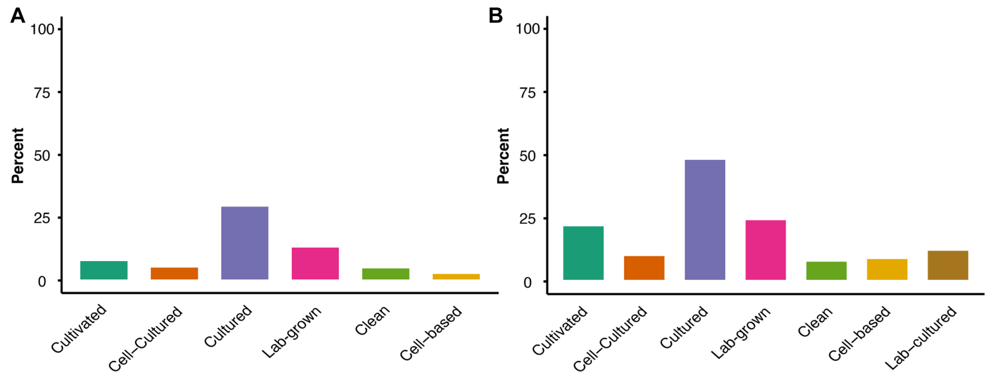

FIGURE 1
Overall percentages of submissions mentioning top label terms. **(A)** Overall percent of comments mentioning each hyphenated and/or preceding label term together with the root term 'meat'. **(B)** Overall percent of comments mentioning each hyphenated and/or preceding label term, analyzed without the root term 'meat'.

organizations mentioned *cell-cultured meat* in 63.6% of comments (Figure 2C). Farmer support non-profits, the affiliation category with the highest number of submission ($n = 37$), mentioned the terms *cell-cultured meat* and *cultured meat* in a moderate percent of submissions (43.2, 48.6% respectively) (Figure 2D). Similarly, *cultured meat* and *cell-cultured meat* were the most frequently (both 75%) mentioned terms for submissions made by animal welfare non-profits (Figure 2F). Those categorized as "other" moderately mentioned *cultivated meat* (50%) and *cultured meat* (40%) (Figure 2G), while those with an unknown affiliation mentioned all terms sparingly (less than 25%), with *cultured meat* being the most commonly used term (28.7%) (Figure 2H). The comments within the unknown affiliation category beginning with "As an Arkansas farmer…" all proposed the term *lab-cultured protein*. Therefore, they did not affect the results in Figure 2, but contributed to the findings of Figure 1B and Supplementary Figure S2 indicating *lab-cultured* as a top hyphenated and preceding label term when analyzed without the root term 'meat'.

Only 3 of the 6 label terms were mentioned across all affiliation categories, namely, *cell-cultured meat, cultured meat,* and *lab-grown meat* (Figure 2). While cell-cultured meat companies, research organizations, farmer advocacy groups, and animal welfare non-profits discussed all top 6 label terms, several affiliation groups completely omitted certain label terms. For example, traditional meat farmers predominately mentioned the terms *cell-cultured meat* and *cell-based meat* (Figure 2B), while omitting the label term *clean meat*. Similarly, government agencies did not mention *cultivated meat* or *cell-based meat* (Figure 2E), and *clean meat* was not mentioned in comments made by the "other" affiliation category (Figure 2G). Comments from unknown affiliations (Figure 2H) and government agencies (Figure 2D) scarcely mentioned any of the proposed labels.

3.3. Tyson foods, with interests in both cell-cultured and traditional meat, proposes three terms: *cultivated, cell-based, cultured*

Our third research question evaluated the comments submitted by Tyson Foods and how their suggested label terms compared to cell-cultured meat and traditional meat professionals. The Tyson Foods submission contained 1,669 words, 4 citations, and no supplemental information. Of the top label terms identified from the overall comments submitted to the ANPR (see Figure 2), only *cultured meat* and *cultivated meat* were mentioned by Tyson Foods. However, their submission mentioned a three-part conjoined term, "*cultivated/cell-based/cultured*" (mentioned 11 times), with the root term mentioned as being "along with the appropriate standard of identity or common or usual name." When discussing these products, Tyson Foods most often referenced them as *cultured animal cells.* This suggests a work-around the existing limitations for cell-cultured meats with regards to the meat standard of identity regulation.

4. Discussion

The present study systematically evaluated comments submitted to a response ANPR that sought public input on cell-cultured meat labeling. Using our research hypotheses that economic interest and affiliation would affect submission extent and quantity, we found an effect opposite of what we expected. Further, the median length of submissions was highest for those without economic interest. This finding may be due to the nature of the organizations without economic ties submitting from the "other" and animal welfare non-profit affiliation categories, as they customarily voice their opinion on government policy. For example, within the affiliation category "other," law students in the Harvard Animal Law and Policy Clinic and the Food Law and Policy Clinic submitted an 18-page response to the ANPR (33). They supported their sizeable comment by indicating the potential implications mandated labeling of these novel products has on First Amendment rights. Within the animal welfare non-profits, groups such as PETA submitted responses of length to express their outlook on the importance of these novel products for animal welfare. Three of the four submissions within this affiliation category responded to the prompted questions by the USDA-FSIS. While these organizations rely on voicing their opinions to guide policy, their lack of economic interest may also compel their extensive submissions as their relevance is not financially motivated, but ethically. Conversely,

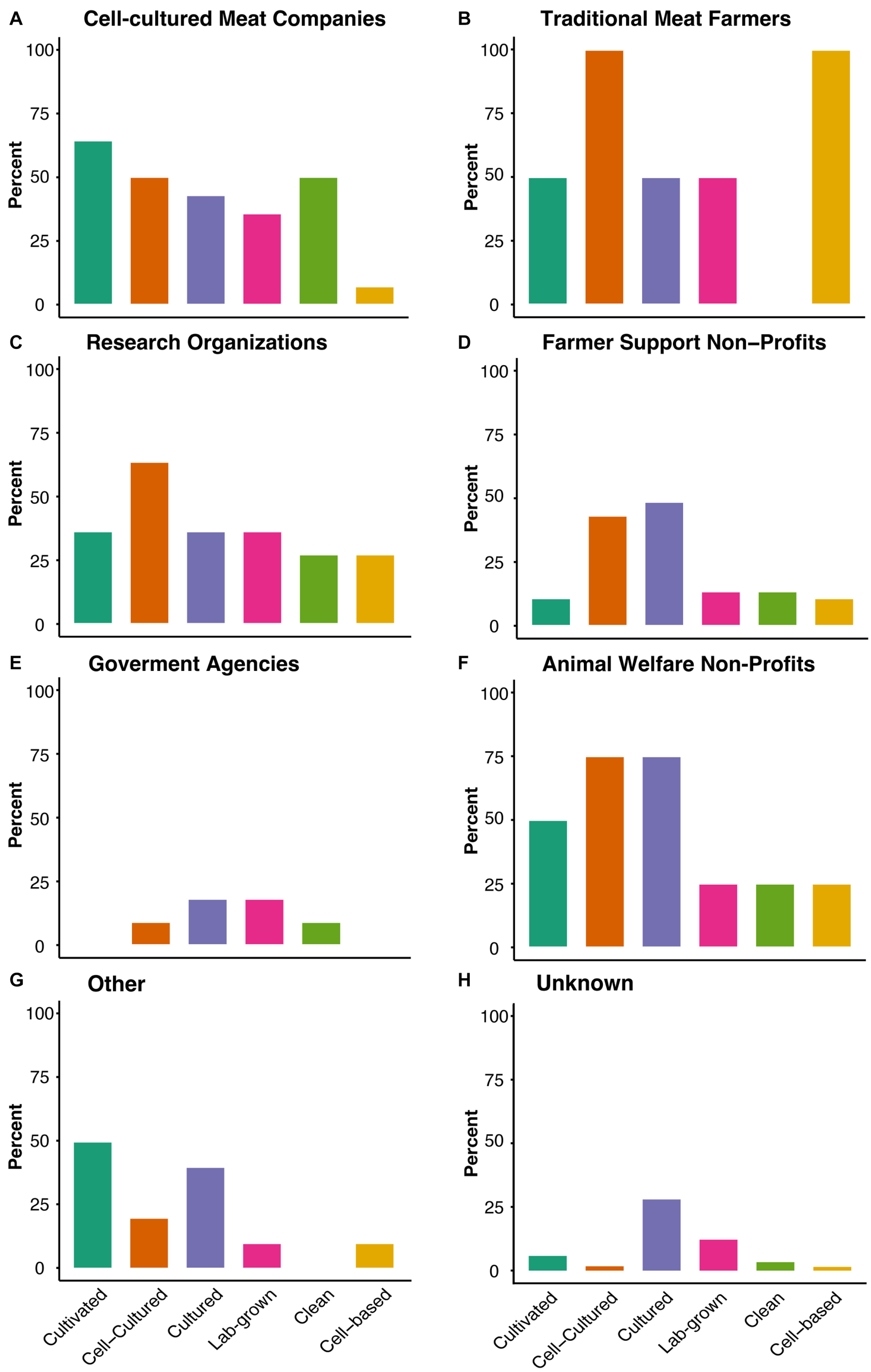

FIGURE 2
Percentages of submissions mentioning top label terms by affiliation. The percentages of submissions mentioning each of the top label terms in conjunction with the root term 'meat' was calculated for **(A)** cell-cultured meat companies (*n* = 14), **(B)** traditional meat farmers (*n* = 2), **(C)** research organizations (*n* = 11), **(D)** farmer advocacy groups (*n* = 37), **(E)** animal welfare non-profits (*n* = 4), **(F)** government agencies (*n* = 11), **(G)** other (*n* = 10), and **(H)** unknown affiliations (*n* = 1,062).

those with economic ties may not feel that it is necessary to support their argument in this manner as they are closely tied to the field, making their opinions inherently relevant.

While identified affiliation and economic interest were not predictors of submission quantity or length of submitted comments, percentages grouped by affiliation identified which types of organizations were most intrigued to submit. In terms of economic interest, we identified an overwhelming number of submissions from those with unknown ties. With this finding, we reject our first hypothesis that those with economic interest will have the highest number of submissions. It is also possible that these submissions chose to not disclose an economic interest. Only a small fraction of submissions were made by non-United States entities. There were 22 international submissions originating from Australia, Canada, Denmark, Germany, Israel, Netherlands, New Zealand, Saudi Arabia, Singapore, Spain, Uganda, and the United Kingdom. Of the international submissions, none had an identifiable organization. However, we found that 3 submissions from Canadian government agencies did not designate a country of origin; it is possible that other submissions did not declare their country of origin.

Interestingly, submissions made by individuals with unknown economic interest were much shorter as indicated by the lowest median word count of roughly a paragraph compared to those with and without economic interest of 1.5–3.5 standard pages. We infer that these submissions (i.e., with unknown ties) may represent the concerns and opinions of everyday consumers on how such products should be labeled. The differences in median word count could also be attributed to the lack of response to each of the 14 proposed rules that the FSIS provided with the ANPR. In general, comments that disclosed the submitting organization were much longer and provided comments on more of the 14 proposed rules – we believe that is reflective of organizational tie, regardless of economic impact.

Our findings regarding what types of affiliations submitted comments identified farmer advocacy groups to be the largest group of commenters with an identifiable organizational tie, submitting more than double the number of comments than the cell-cultured meat industry. It is apparent that these organizations likely voiced group opinions of traditional meat farmers as direct submissions from traditional meat farmers were minimal. Of the various farmer advocacy groups, it is known that the United States Cattlemen's Association (USCA) is petitioning against the use of the term *meat* within labeling of meat alternative products, evidenced by their 2018 submitted petition to the FSIS to establish meat labeling requirements. This petition did not receive a response until 2021, in which the reply resulted in the release of the ANPR evaluated in this paper (34, 35). This suggests that the traditional meat industry has recognized cell-cultured meat commercialization as a significant impact to their livelihood and economy. Further, they advocate for transparent labeling that does not negatively impact profits of traditional meat products.

Our text analysis results identified several potential label terms for these novel food products, both with and without the root term 'meat'. This forms a basis to further explore suitable labels. We quantified the percentages of label terms mentioned by each affiliation, which may provide evidence of how these affiliation groups differ in discussing these products. For example, the omission of *clean meat* by traditional meat farmers and the "other" affiliation category indicates that these groups do not identify it to be a potential label. We also found that all top 6 label terms were mentioned similarly when analyzed with and without the root term 'meat', which could indicate a labelling strategy including these hyphenated and preceding terms that would circumvent the potential restrictions of use of the term 'meat'.

Our investigation of the most widely mentioned label terms allowed for visualization of the diversity in discussion of these novel products. Overall, *cultured meat* was mentioned in about 1/3 of comments, the highest percent of all top label terms identified (Figure 1A). However, when analyzing terms by affiliation category, differences in percentages of label mentions became apparent (Figure 2). Cell-cultured meat companies frequently mentioned the term *cultivated meat*, whereas traditional meat farmers frequently mentioned the terms *cell-cultured meat* and *cell-based meat*. This suggests that these two industries, thought to have directly opposing viewpoints, reference these products with different terminology. Our finding supports our second hypothesis regarding differences in predominant label terms mentioned in comments by these two affiliation categories. Further, the percent mentions by farmer advocacy groups revealed partial alignment with submissions by traditional meat farmers through similar percentages mentioning *cell-cultured meat*. The predominant labels *cultured meat* and *cell-cultured meat* by animal welfare non-profits may provide insight of how these products are being discussed by those who feel passionately about animal welfare. The scarcity of label mentions by government agencies and the unknown affiliate group makes it difficult to identify how these products are being discussed by these affiliations. However, from Supplementary Figure S2 it is apparent that these affiliation categories referenced these products primarily using the preceding term *cultured,* indicating use of a different root term or no root term at all.

We speculate that the hyphenated term *cell-among* the predominant label terms mentioned by traditional meat farmers, may indicate a preference for technology-oriented terminology. While labeling these products using the term *cell-has* been shown to increase consumer understanding, it may elicit a negative consumer response related to food technology neophobia, or perceived naturalness of these products (36). Further, the lack of the term *clean meat* in submissions made by traditional meat farmers may be due to the adverse effects that labeling cell-cultured meat as *clean meat* would have on the perception of traditional meat (inferring that traditional meat may be "unclean" or "dirty"). A recent study by Malerich & Bryant also scanned submissions to the ANPR to identify different labels for their consumer research study. They sought to identify consumer perception of the various label terms with regards to transparency, appeal, purchase intent, and perceived safety (16). While using the prefix '*cell-*' increased consumer understanding of the product, however, appeal, purchase intent, and perceived safety for beef products was highest when presented with the term *cultivated meat* (16). As this term is the predominant label term mentioned by cell-cultured meat companies, we speculate that cell-cultured meat companies are proposing labeling of these products with more appealing terminology. Due to the limited analysis of the ANPR comments in Malerich & Bryant's – in which they used an online tracker which only contained comments with an identifiable organization tie, and only analyzed the preceding label term, there are differences in the overall hierarchy of label terms identified in their and our study. Nonetheless, their findings confirm 5 of the top 6 labels we identified, with the except of the term *clean meat*, which we identified to be mentioned in 5% of comments.

We analyzed the submission by Tyson Foods separately due to their affiliation with both the traditional and cell-cultured meat industry. Their proposal of three potential terms *cultivated/cell-based/cultured* provides a term for each parameter of importance for a label:

appeal (*cultivated*), understandability (*cell-based*), and neutrality (*cultured*) (37). Interestingly, each label term within the three-part conjoined term relates to the predominantly mentioned label terms by cultivated meat companies, traditional meat farmers, and overall submissions, respectively. Our findings suggest partial alignment with our hypothesis, namely, that Tyson Foods references these products using labels similar to those suggested by traditional meat farmers. However, we identified that the labels mentioned by Tyson were used by both traditional meat farmers and cell-cultured meat companies, which is opposite to what we initially hypothesized. Advantages and disadvantages for these three potential labels have been previously researched (38–41). While the term *cultivated meat* was found to provide greater consumer appeal, the term *cell-based meat* was more clearly understood (22). Label transparency was evaluated in a recent study by Hallman et al. (42). They also found that labels including the term "cell-" were more easily differentiated from traditional meat by a sample of 4,385 US consumers (42). Therefore, we speculate that major players within the cell-cultured meat industry may opt for a label that is both transparent and appealing to consumers.

Prior research has explored the use of different label terms with the public and measured consumer understanding, acceptance, perceived safety, and likelihood to purchase (16, 22, 43–45). Regardless of the lack of specified label terminology for such food products, a study in New Zealand suggested cell-cultured meat to be "rebranded as *clean meat,*" as recent studies demonstrated this label term was highest in positive consumer attitude and acceptance (45). While it is argued that this label leads to higher consumer acceptance, it is not recognized as being a neutral term and may create a negative bias on the traditional meat farming industry (22). The Good Food Institute (GFI) previously encouraged the use of the term *clean meat*, placing an emphasis on the importance of consumer appeal over neutrality and consumer understanding of the label (with the basis of all labels meeting a minimum standard of neutrality) (37). GFI provided one of the longest submissions to the ANPR with the most substantial supplemental materials (6 sections, 118 pages). While we were expecting submissions from academic researchers working in this area, we could not identify submissions from individuals working and publishing in the field. The submission from the Harvard Animal Law & Policy Clinic/Harvard Food Law & Policy Clinic on behalf of five academic researchers affiliated with this group, was the longest within the research organizations affiliation category and contained the largest number of scientific references. The most common term used throughout this submission was *cultivated meat.* In terms of relation to common everyday language, a paper evaluating tweets for mentions of cell-cultured meat indicates that *meat, cultured, cell, based, cultivated, clean,* and *cells* were among the top words used on Twitter about cell-cultured meat in the United States (46). This reinforces the focal points of a suitable label that were outlined previously and reiterates that the terms identified from social networks and the ANPR alike are commonly used among consumers and thus, provide understandable labeling strategies.

We analyzed all top preceding label terms (e.g., *cultured, cultivated, cell-cultured*) with and without the term meat. Previous research has shown that inclusion of the word *meat* does not play a significant role in consumer understanding (47). However, identifying these products as meat has implications for the standards of identity for meat and meat products as outlined in the introduction. This has become increasingly important with the commercialization of cell-cultured meat; the FSIS sought specific inputs on this issue in questions 7, 8, 10, and 11 (see Supplementary Table S1). As stated previously, not every submission provided comments on these specific questions. It is unclear why, but nonetheless, to use the term *meat* for these products, they either are recognized as meat under the current version of the CFR, or the CFR must be widened to encompass also cell-cultured meat. While cell-cultured meat has the potential to be recognized as a meat preparation process, to distinguish between cell-cultured meat and traditionally farmed meat, changes to 9 CFR317.2 to allow for cell-cultured meat labeling may in turn force the traditional meat industry to label their products as well. These labels may include terms such as "traditionally slaughtered" or "traditionally processed." While the USDA-FSIS has not provided any follow-up announcements regarding the labeling of these products, it is currently stated on their website that "FSIS will ensure that cell-cultured products are labeled truthfully and consistent with coordinated FDA and FSIS labeling principles… FSIS does intend to publish new labeling regulations for such products" (48).

To further understand the use of the preceding terms by affiliation categories, we evaluated the percentage of comments for each preceding term of the top label terms (see Supplementary Figure S2). The majority of affiliation groups referenced all top preceding terms in at least 25% of submissions. While our analysis of label terms including the word *meat* revealed lower percentages of submissions referencing these terms, this may be attributed to the variety of root terms used (e.g., *protein, chicken, beef, cultured animal cells*). We also found that some submissions discussed using only the preceding term without a root term. Overall, proposed label term constructs varied in hyphenated, preceding, and root terms (see Supplementary Table S3). Those in support of cell-cultured meat commercialization often proposed consumer friendly label terms containing the root term 'meat' and used hyphenated and/or preceding terms such as *slaughter-free, ethical.* Those opposing commercialization often expressed that the term 'meat' should not be used to discuss these products. This may be due to the perception of these products as unnatural (49). Others felt that the term 'meat' was suitable, but in conjunction with preceding and/or hyphenated terms that may trigger disgust or neophobia within consumers (e.g., *synthetic, fake*) (36, 45). Further, some comments proposed novel terms (e.g., cegan, meatalin). Our findings exemplify the diversity in opinions on how these products should be labeled regarding all portions of label constructs (i.e., hyphenated, preceding, and root terms).

While a portion of submitters feel that these novel products should not be labeled with the root term 'meat', a similar case lies with plant-based meat and milk alternatives. The FDA has yet to establish appropriate labeling guidelines for these products. In January 2019, the National Milk Producers Federation (NMPF) submitted a comment to the FDA regarding the use of the word "milk" in plant-based products (32). The impact of labeling terminology on consumer choice and understanding of the nutritional value of plant-based milk products has reached significant concern at the level of the US government. In April 2021, the Dairy Pride Act was introduced in the Senate to enforce against misbranded milk alternatives (50). In 2022, the FDA has listed both of these topics as a part of the "Foods Program Guidance Under Development" (51). Draft recommendations for "the naming of plant-based foods that are marketed and sold as alternatives to milk" was released February 22, 2023, which ultimately allows for these products to be sold as "milk" and recommends a voluntary nutrient statement (52). No further recommendations have been made regarding the labeling of plant-based meat.

Due to the unique nature of our data sourcing, several limitations of our study exist. The low submission count from traditional meat farmers, in contrast to farmer non-profits and cell-cultured meat companies, impacts our comparison of label use rate between affiliate groups. Another limitation is our inability to identify organizational ties for the vast majority of submissions. Although it could be that these anonymous submissions were provided by everyday consumers, we can only assume these comments represent consumers' attitudes toward labeling of cell-cultured meats. A limitation of our study design is that we quantified the percentage of label mentions rather than the direction of the statements relative to the labels (i.e., positive vs. neutral vs. negative sentiment). Sentiment analysis and other emotion analysis approaches could be performed to further understand negative and positive associations for each proposed label (53). This could consist of further identifying the support, or lack thereof, for each identified most common label term per submission.

Here, we set out to analyze the composition, extent, and disclosure of USDA ANPR submissions for the labeling of cell-cultured meat and poultry products. We identified several potential label terms for consideration. Future studies will evaluate each label term for consistency, transparency, and consumer acceptability. This may help explain *why* consumer appeal varies by label as evidenced by several studies (11, 29, 33). Once cell-cultured meat products are available for tasting, research on the interaction between label terms and perception will provide further insights into consumer acceptance of novel food products.

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

MF, HH, and JW conceived and designed the study. MF performed all text and statistical analysis with support from HH and JW. MF wrote the manuscript with input from HH and JW. HH and JW supervised the project. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2023.1197111/full#supplementary-material

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A *taste* of cell-cultured meat: a scoping review

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Cell-cultured meat (CM) is a novel meat product grown *in vitro* from animal cells, widely framed as equivalent to conventional meat but presented as produced in a more sustainable way. Despite its limited availability for human consumption, consumer acceptance of CM (e.g., willingness to purchase and consume) has been extensively investigated. A key but under-investigated assumption of these studies is that CM's sensory qualities are comparable to conventional, equivalent meat products. Therefore, the current review aims to clarify what is actually known about the sensory characteristics of CM and their potential impact on consumer acceptance. To this end, a structured scoping review of existing, peer-reviewed literature on the sensory evaluation of CM was conducted according to the PRISMA-ScR and Joanna Briggs Institute guidelines. Among the included studies ($N = 26$), only 5 conducted research activities that could be termed "sensory evaluation," with only 4 of those 5 studies evaluating actual CM products in some form. The remaining 21 studies based their conclusions on the sensory characteristics of CM and consequent consumer acceptance to a set of hypothetical CM products and consumption experiences, often with explicitly positive information framing. In addition, many consumer acceptance studies in the literature have the explicit goal to increase the acceptance of CM, with some authors (researchers) acting as direct CM industry affiliates; this may be a source of bias on the level of consumer acceptance toward these products. By separating what is known about CM sensory characteristics and consumer acceptance from what is merely speculated, the current review reported realistic expectations of CM's sensory characteristics within the promissory narratives of CM proponents.

KEYWORDS

cultivated meat, sensory evaluation, consumer acceptance, meat alternative, scoping review

1 Introduction

Cell-cultured meat (CM), also known as "lab-grown," "*in-vitro*," "cultured meat," "cultivated meat," "clean," "synthetic," "artificial," and "cell-based" meat is a meat alternative grown *in vitro* from animal cells using tissue engineering techniques (1, 2). The concept of growing cells *in vitro* was first introduced in 1912 (3), but began to be intensively developed to be used in meat production in the early 2000s (1, 4–6). CM development has been justified for various reasons, from creating a novel food-source for long-term outer space expeditions to ensuring food security in the developing world. Of these, ensuring food sustainability and reducing the environmental impact of current agricultural practices are the two most frequently proposed reasons for developing CM (7–9).

As of mid-2023, over 100 companies worldwide have been involved in the development of CM, both in the meat production from cell lines as well as in lowering the cost of essential components (e.g., growth media or fermentor design) of this technology (10). However, the presence of CM in the market is still very limited. Recently, food agencies in the United States (USDA and FDA) have released regulations regarding human foods made using animal cell culture, and some CM companies (e.g., Upside Foods and Good Meat Inc.) have gained permission to market their products. So far, CM sales have only been approved in the United States and Singapore (11, 12).

Cultured meat has captured the public and scientific imagination across multiple fields. Beyond the technical and scientific challenges to developing such a novel biotechnology, perspectives, challenges, and developments on the topic have frequently been reviewed across many disciplines, from its environmental impacts to the current and possible consumer response to this kind of product (6, 10, 13). Consumer acceptance is a key determinant for the success of any novel food product (14, 15). Therefore, despite its still-extremely limited presence in the marketplace, many studies have been conducted to examine different determinants of consumer acceptance of CM worldwide (15–17). Attitudes toward the biotechnology itself have been studied through survey methodology, as well as the impact of other factors such as consumer demographics (e.g., age, gender, and nationality), psychological characteristics of the consumers (e.g., food neophobia or disgust), and information framing and promissory characteristics around the product [e.g., "Cultured meat is the only alternative to regular meat that consists of real meat. It therefore has the same taste, odor, tenderness, juiciness and mouthfeel as regular meat"; (18), p. 4]; these factors have been evaluated as potential determinants of consumer acceptance (6, 16, 18, 19). Among the tested factors, 'having similar sensory characteristics as conventional meat' consistently emerged as a determinant of stated consumer acceptance (20–22).

Meat flavor and texture (tenderness) are the most important sensory characteristics that determine consumer acceptability and purchasing decision of meat products overall (23–25). The limited room for compromise on meat palatability and eating experiences may be a key barrier for consumer adoption of meat substitutes (22, 26, 27). This challenge is especially relevant for CM as it is typically positioned as having the same sensory qualities and functionalities of conventional meat because it is chemically and, in some sense, biologically equivalent (18, 28–30). Because it is arguably "real meat," it is extremely important that the sensory characteristics of CM align with those expected by consumers for typical meat products. However, due to the extremely limited availability of CM, knowledge of CM sensory characteristics is largely hypothetical, based on CM researchers' and proponents' own reports and consumers' imaginations (28, 31–33).

As the body of literature around CM has grown rapidly, a number of reviews have been published within the broad topic of consumer acceptance of CM (34–36). However, none of these reviews have focused on this topic from the perspective of sensory science to answer critical questions: what are the observable or measurable sensory characteristics of CM, and how are those related to consumer acceptance of CM? Therefore, a scoping review was chosen as a tool to explore the current state of knowledge regarding the sensory characteristics of CM. Scoping reviews are used to map the key concepts and available evidence underpinning a research area (37). This study aimed to identify what is directly known about how CM tastes, how CM is *expected* to taste, and how consumers respond to those sensory characteristics in imagination or reality.

2 Materials and methods

2.1 Protocol, main question, and definition

This scoping review aimed to answer the question "What are the known sensory characteristics of CM and how have those characteristics been evaluated?" The Preferred Reporting Items for Systematic Reviews and Meta-Analyses guideline for scoping review (PRISMA-ScR) was used as a reporting guideline with the Joanna Briggs Institute (JBI) guidance as the methodological guideline (38). The inclusion and exclusion criteria were defined with an emphasis on the presence of comments on the sensory characteristics of CM regardless of actual product evaluation. CM was defined as a meat alternative produced through animal cell culture to grow meat *in vitro*.

2.2 Eligibility criteria

The literature included in this study are peer-reviewed journal articles published between the years 2000 and (June) 2023. The date range was chosen because, even though the concept of CM was introduced in 1912 (4, 5), the approach was not used to produce meat until the early 2000s. To be included in this review, articles had to meet the following criteria:

1. Must be a scholarly (peer-reviewed) publication.
2. The concept or product of cell-cultured meat (defined as "a meat alternative grown *in vitro* from animal cells") is involved in the study, exclusively or compared to other meat alternatives.
3. Investigates or describes at least one *sensory* characteristic of cell-cultured meat. For this review, we defined sensory characteristics to be both analytic and affective: descriptions of taste or flavors as well as affective responses.
4. Article is written in English.
5. Articles published between January 1, 2000 and June 11, 2023.

Studies with the following characteristics were excluded:

1. Review or non-original research articles. Although not included, citation chasing was conducted on retrieved review articles to ensure maximum scope.
2. Articles focused only on the technical production of cell-cultured meat without evaluation by human subjects.
3. Studies only investigating other meat alternatives (e.g., plants, insects, fungi, etc.).
4. Articles not written in English.
5. Articles published before January 1, 2000.

2.3 Information sources and search strategy

Articles from peer-reviewed publications were the primary studies used for this scoping review. The primary studies were retrieved through electronic searches of the following databases: Web of Science Core Collection (WOSCC; Web of Science), Food Science and Technology Abstracts (FSTA; EBSCOhost), and Center for Agriculture and Bioscience International (CABI; CAB Abstracts).

With support and feedback from the University Libraries at Virginia Tech (author CC), the following search strategy was developed iteratively to ensure optimal search results. The final search string as applied in Web of Science is shown in Table 1.

Title, abstract, and keywords search was conducted for all concepts in WOSCC and FSTA; all fields were searched in CABI. In all databases, limits were applied using built-in filters for document type (journal article) and publication year (Appendix 1). The format of this search string was modified for application on the other databases. Appendix 1 contains the detailed search strings used in each database. The initial search was performed in January 2023. Considering the rapid increase in publications on CM, monthly searches were performed in each database until June 2023 - the original search strings were reapplied to each database, but limited to (using built-in filters) from 2022 to 2023 to reduce the number of duplicate results. The work cited by articles that were related to topic but did not fully meet criteria (and were excluded) were scanned for additional relevant records (backward citation chasing).

2.4 Record screening and data extraction

All search results were exported from each database and imported into the systematic review management software Covidence (39), where duplicates identified by the software were removed automatically. Screening proceeded in stages detailed in Figure 1. First, the studies were screened based on the title and abstract, and obviously irrelevant studies were excluded. The full-text of potentially relevant studies was collected and further examined to ensure the studies met eligibility criteria (see Section 2.3). Both title and abstract screening and full-text screening were conducted by two independent reviewers (KT and JL). Discrepancies were resolved through discussions.

Data extraction was conducted in Covidence using a data extraction template developed by the authors. The full data extraction form is attached as Appendix 2. Data extracted included general information (e.g., article title, authors' name and affiliations, publication year, and DOI), country in which the study is conducted, framed value of CM, sampling methods, survey/sensory evaluation methods, types of sample tested, sensory/acceptance measures, and proposed determinant factors toward CM acceptance, among others.

TABLE 1 Search string to identify literature related to cell-cultured meat sensory characteristics in Web of Science, January 20, 2023.

1	("culture? meat" OR "cultivate? meat" OR "lab-grown meat" OR "cell-based" OR "clean meat" OR "*in-vitro* meat" OR "artificial meat" OR "synthetic meat" OR "cell* meat")
2	(accept* OR attitude OR preference OR perception OR fram* OR willingness OR awareness OR liking)
3	(taste OR texture OR flavo?r OR appearance OR look OR sensory)
4	#1 AND #2 AND #3

?: To retrieve words with the replacement of 1 character; *: To retrieve words with variant zero to many characters.

The extraction was focused to identify information related to the expected or actual sensory characteristics of CM, the evidence/experiment supporting the claim, and the determining factor(s) of CM acceptance. Relevant data were extracted by one author (KT) and reviewed for consistency by a second author (JL).

3 Results

The results encompass descriptive characteristics about each study, author-hypothesized determinants of CM acceptance among consumers, and consumer-reported sensory experiences of CM. Consumers' perceptions of CM's sensory experiences were treated according to the study method and whether or not they evaluated actual CM samples.

3.1 Description of sources

A total of 491 citations were obtained from the database search (WOS = 386 articles, CABI = 50 articles, FSTA = 55 articles) and 4 articles from backward citation chasing. Once duplicates were removed, 303 articles were screened by title and abstract. This first screening excluded 238 publications that were found to be irrelevant to the review objectives. Full texts of the remaining publications were then evaluated according to the eligibility criteria; 43 publications were excluded. Finally, 22 publications from the database search and 4 publications from backward citation chasing were included in the review, resulting in a final count of 26 publications (Figure 1).

Information about each study's characteristics is presented in Table 2. Of the studies included in this review, most involved participants from the "Global North": Europe ($N = 21$ studies) and North America ($N = 7$ studies). A minority involved participants from Asian countries ($N = 5$ studies), Australia ($N = 1$ study), and New Zealand ($N = 1$ study). No studies involved participants from countries in South America or Africa. Typically, subjects were selected using simple, random sampling ($N = 15$ studies) or convenience sampling ($N = 7$ studies). Most studies employed online surveys ($N = 21$ studies) while only 2 studies used in-person, paper questionnaires. Qualitative methods (interviewing and focus groups) were in the minority of the selected studies ($N = 3$ studies) and only 5 studies conducted an actual sensory evaluation—using human subjects to assess some aspect of the sensory properties of a food product—to evaluate CM products.

Although by definition of the search strategy all papers were related to the sensory evaluation of CM, the most common research question was only tangentially related to sensory evaluation: consumers' "willingness to try/eat" ($N = 17$ studies) and "willingness to buy" ($N = 11$ studies) CM were the main acceptance measures used among the included studies. Some studies measured their participants' willingness to replace conventional meat ($N = 4$ studies) or other meat alternatives ($N = 2$ studies) with CM and their willingness to recommend CM to other people ($N = 2$ studies) to support their studies. Through close reading of study objectives, we concluded that evaluating the sensory properties of CM was considered a primary outcome in 6 studies, while 2 studies inferred the importance of CM's sensory properties. The majority ($N = 18$ studies) included sensory evaluation as a secondary outcome.

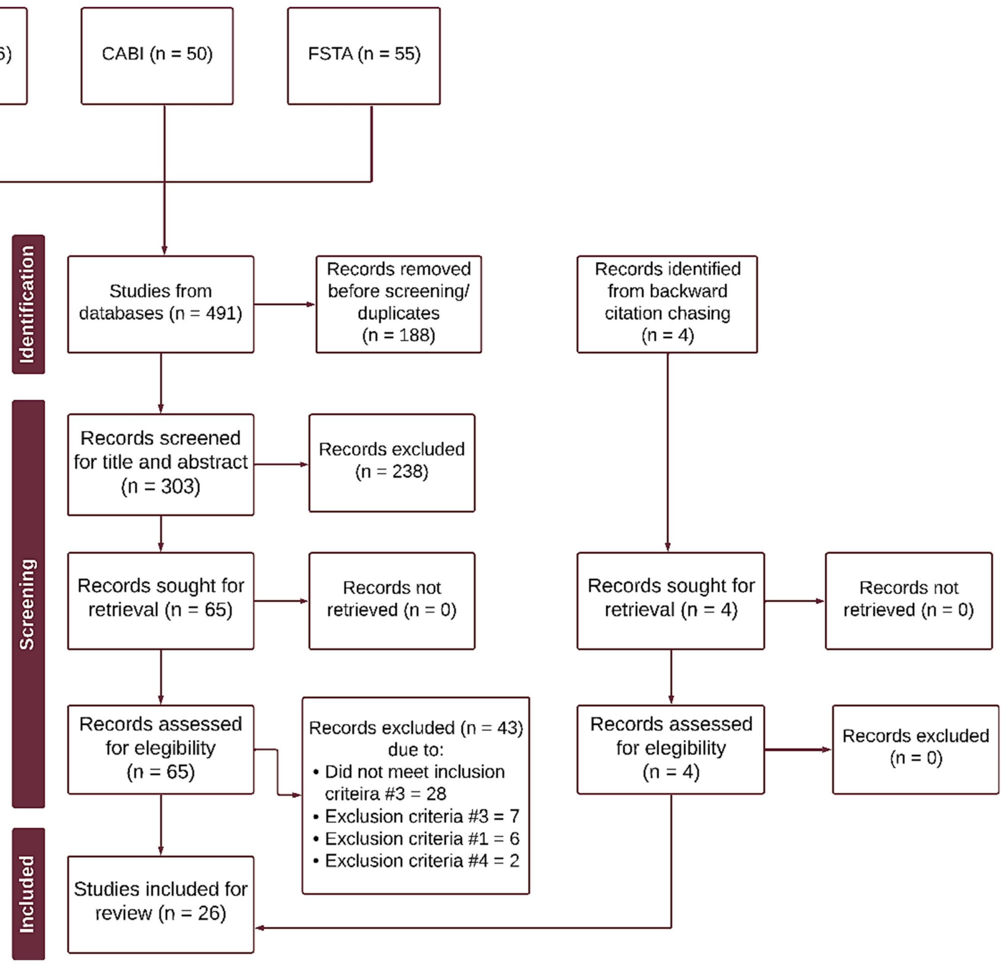

FIGURE 1
PRISMA flow diagram of the scoping review process. Inclusion criteria #3: Investigates or describes at least one sensory characteristic of cell-cultured meat. For this review, we defined sensory characteristics to be both analytic and affective: descriptions of taste or flavors as well as affective responses. Exclusion criteria #3: Studies only investigating other meat alternatives (e.g., plants, insects, fungi, etc.). Exclusion criteria #1: Review or non-original research articles. Although not included, citation chasing was conducted on retrieved review articles to ensure maximum scope. Exclusion criteria #4: Articles not written in English.

3.2 Hypothesized determinants for consumer acceptance of cell-cultured meat

The majority of the included studies examined consumers' attitudes toward CM as a food product (i.e., instead of as a technology or a social innovation). Each paper opened by reporting positive actual or (frequently) potential impacts of CM (Table 3). Most proposed CM as part of a solution to reducing environmental pollution ($N=22$ studies), minimizing the use of natural resources ($N=18$ studies), promoting animal welfare ($N=19$ studies), or promoting food security ($N=7$ studies) along with fulfilling the increasing demand for animal proteins ($N=6$ studies). CM was also said to have the same or possibly better nutritional value ($N=8$ studies), to be safer to consume than ($N=11$ studies), and to have the same sensory characteristics as conventional meat ($N=6$ studies).

Despite these proposed possible benefits of CM from the studies' authors, the factors measured in these studies and consumer responses often indicate alternative and more negative perspectives. Table 4 presents various factors that authors explicitly or implicitly hypothesized as impacts on consumers' acceptance of CM. Common author-hypothesized determinants include views of animal welfare ($N=11$ studies), concern over environmental impact of CM and the current systems of meat production method ($N=13$ studies), familiarity and curiosity toward CM ($N=11$ studies), perception of naturalness of CM ($N=6$ studies), and psychological factors related to the individual such as food neophobia and disgust ($N=10$ studies). The need to evaluate these determinants indicates that the authors of these studies are concerned with and well aware of alternatives to the positive narratives and impacts proposed in the introductions to these studies. Moreover, participants frequently mentioned concerns about CM's health impacts, nutrition quality, or food safety ($N=18$ studies) and, often, the sensory properties of CM (e.g., how it would taste, $N=18$ studies), indicating that consumers echoed some of the concerns about whether CM will be a universally positive replacement for conventional meat products.

TABLE 2 Characteristics of the included studies based on geographic location, participants selection method, survey method, product (cell-cultured meat) acceptance measures, and if sensory evaluation of cell-cultured meat was considered the main outcome of the study.

Country of studies		Number of studies[a]	References
Belgium	Europe	2	(40, 41)
Croatia		1	(42)
European Union		1	(33)
Finland		3	(22, 40, 43)
Greece		1	(42)
Italy		1	(44)
Netherlands		3	(18, 20, 45)
Poland		1	(20)
Portugal		2	(40, 46)
Spain		2	(20, 42)
United Kingdom		4	(20, 33, 40, 47)
Canada	North America	2	(48, 49)
United States		5	(7, 33, 50, 51, 52)
Israel	Asia	1	(53)
Japan		1	(54)
Singapore		2	(21, 55)
Turkey		1	(19)
Australia	Australia	1	(56)
New Zealand		1	(57)
Participants selection method			
Random sampling		15	(18, 20, 33, 40, 44, 46, 47, 49, 50, 51, 52, 53, 54, 56, 57)
Convenience sampling		8	(7, 19, 22, 41, 43, 45, 48, 55)
Snowball sampling		1	(42)
Stratified sampling		1	(21)
N/A[b]		1	(58)
Survey method			
Online questionnaire		21	(18–21, 33, 40–51, 52, 54, 55, 56)
Paper questionnaire/ handouts		2	(53, 57)
Interview/ group discussion		3	(40, 56, 57)
Meat product evaluation		5	(7, 18, 53, 55, 58)
Cultured meat acceptance measures			
Willingness to buy		11	(18, 21, 41, 42, 44, 47, 48, 49, 51, 52, 57)
Willingness to replace conventional meat		4	(21, 48, 51, 53)
Willingness to try/ eat		17	(18, 19, 21, 20, 33, 40, 41, 42, 43, 44, 45, 48, 50, 51, 52, 56, 57)
Willingness to reduce meat consumption		3	(20, 21, 42)
Willingness to replace other meat alternatives		2	(21, 48, 51)
Willingness to recommend to others		2	(19, 56)
Sensory attributes as a primary outcome			
Primary		6	(18, 43, 47, 53, 55, 58)
Secondary		18	(7, 19, 21, 22, 33, 40, 41, 42, 45, 44, 46, 48, 49, 50, 51, 52, 54, 57)
Inference		2	(20, 56)

[a]More than one response could be selected for a study. Thus, the total number of studies in each category may exceed the total number of included studies ($N = 26$).
[b]The corresponding study evaluated their samples instrumentally.

TABLE 3 Author signified values of cell-cultured meat that are emphasized in the introduction or hinted throughout the study.

Value framing	Number of studies[a]	References
Reduce environmental pollution	22	(18–22, 33, 40–44, 46–58)
Promote animal welfares	19	(18, 19, 22, 33, 40, 41, 42, 44, 45, 47, 48, 50, 51, 52, 54, 56–58)
Minimize the use of natural resources	18	(18, 20–22, 41, 44–54, 56–58)
Safer to consume than conventional meat	11	(18, 21, 22, 33, 40, 41, 42, 46, 47, 48, 53, 59)
As/ more nutritious than conventional meat	8	(18, 33, 41, 46, 47, 48, 50, 55)
Food security	7	(19, 21, 40, 41, 54, 56, 58)
Fulfill increasing demand of animal proteins	6	(18, 33, 41, 44, 56, 58)
Have the same sensory attributes/ experience as conventional meat	6	(18, 19, 49, 50, 52, 55)
Replace conventional meat	6	(33, 40, 42, 48, 51, 52)
Potential biodiversity loss	2	(20, 21)
Reduce meat consumption	1	(57)
Food source for outer space expeditions	1	(7)
Less familiar to the public	1	(43)

[a]More than one response could be selected for a study. Thus, the total number of studies in each category may exceed the total number of included studies (*N* = 26).

3.3 Perceived sensory experience of CM among tested consumers

Because most of these studies examined consumers' holistic attitudes toward CM, it could be argued that understanding the sensory characteristics of CM was not the primary focus of the studies' research designs. However, 18 out of the 26 included studies stated explicitly that sensory experience is a key determining factor for acceptance of this (or any) novel food product. When measuring participants' willingness to accept CM, the questions were always framed to compare CM to conventional meat or meat products. This is implicitly a sensory comparison in the context of a consumer choice study. Unless the type of CM was specified (e.g., cultured seafood), CM was generally compared to a red meat or red meat product. In the reviewed articles, sensory experiences of CM among consumers were evaluated under two conditions: in the absence or the presence of actual products (Table 5).

3.3.1 Sensory characteristics in the absence of product evaluation

The majority of the included studies (*N* = 21 studies) did not involve subjects evaluating any actual meat samples, conventional or CM. The studies instead examined consumers' *expectations* of CM sensory experiences by provoking participants' imaginations: 2 studies asked consumers directly about their expectations for CM taste, and another 19 asked this question after providing an information frame (by words and/ or images) that was meant to affect consumers' expectations. A number of studies reported that participants did not believe that CM would be as tasty as conventional meat and CM products were described as unappealing, disgusting, and were not considered as meat (*N* = 9 studies). Moreover, when compared in a variety of preference-ranking methods to other meat alternatives (e.g., soy- and other vegetarian products, insect-based proteins), CM was often placed at the bottom of the preference rankings along with insect-based alternatives, and consumers seemed to prefer the concept of plant-based alternatives (*N* = 7 studies).

TABLE 4 Factors hypothesized (by authors) as determinants of cell-cultured meat acceptance among potential consumers.

Factors	Number of studies[a]	References
Health/ nutrition/ safety	18	(18, 19, 21, 22, 33, 40, 42–44, 46–54, 56)
Taste (tasty, have the same sensory experience as conventional meat)	18	(19, 20, 21, 22, 40, 41, 42, 44, 45, 46, 47, 48, 50, 53, 54, 56, 57, 58)
Environmental impact	13	(19–22, 40–46, 49, 51)
Animal welfare	11	(19, 21, 22, 41, 42, 44, 45, 48, 49, 51, 57)
Consumer knowledge about cultured meat	11	(18, 20, 42, 43, 45, 46, 48, 50, 51, 56, 57)
Psychology (food neophobia, disgust, belief in technology/ attitude)	10	(18–21, 40, 43, 45, 47, 48, 54)
Economic (price, income)	10	(19, 20, 40, 41, 42, 48, 49, 51, 56, 57)
Framing/ labeling	8	(18, 33, 44, 45, 46, 48, 50, 52)
Naturalness	6	(19, 40, 41, 45, 54, 56)
Demographic background	5	(22, 33, 49, 51, 57)
Convenience	3	(20, 40, 56)
Media coverage (including social media)	1	(22)

[a]More than one response could be selected for a study. Thus, the total number of studies in each category may exceed the total number of included studies (*N* = 26).

In a large minority of studies (*N* = 8), consumers responded positively toward CM as a meat product. Typically, the positive attitude was in response to positive information framing pertaining to product labeling (50), safety and health benefits (44), impact on the environment and animal welfare (45), or perceived naturalness

TABLE 5 Methods used to obtain consumers' perception of CM's sensory experience with and without a physical sample.

How is opinion generated?	Framing theme	Number of studies[a]	References
Direct question of how they think CM would taste (no framing)		2	(21, 43)
Meat sample evaluation		5	(7, 18, 53, 55, 58)
	Others (e.g., economic, technology, sensory characteristics, societal, ethics)	19	(18, 19, 33, 40–42, 44–51, 52, 54, 56, 57)
Positive framing	Health/ safety	13	(18, 19, 33, 40, 42, 44, 46–51, 56)
	Animal welfare	9	(19, 41, 42, 44, 45, 48, 49, 51, 57)
	Labeling	8	(18, 33, 44–46, 48, 50)
	Environmental benefits	6	(19, 41, 42, 44, 49, 51)
	Naturalness	5	(40, 41, 45, 54, 56)
	Meal setting & placebo panel	2	(18, 46)

[a]More than one response could be selected for a study. Thus, the total number of studies in each category may exceed the total number of included studies (*N*=26).

(40) - especially in regards to the production process. The overall measure of acceptance was mainly based on increases in participants' willingness to try and willingness to buy or pay for CM along with individual perception ratings of tested factors listed in section 3.2 (*N*=6). Decrease in disgust perception of CM and increase in perceived similarity of CM with conventional meat products were also considered positive responses (*N*=4). Introducing CM in familiar meals and providing placebo samples to provoke the idea of sensorial similarity of cultured to conventional meat was reported as effective in increasing tested participants' acceptance of CM (*N*=2 studies).

3.3.2 Sensory characteristics based on product evaluation

Actual evaluations of some sort of CM-relevant product were conducted in only 5 out of the 26 studies, with 1 study using a placebo sample and 4 studies evaluating an actual CM sample. Commercially produced beef was used in the placebo sensory testing while the CM samples were made in-house by the researchers. A detailed summary of each study's method and key findings is presented in Table 6.

Rolland et al. (18) conducted a sensory evaluation using placebo samples to gage consumers' likely response to CM with sensory qualities identical to conventional meat. In this experiment, Rolland et al. (18) evaluated participants' initial responses to the concept of CM and then measured changes to those responses after presentation of one of three positive information framings on the *societal, personal,* or *sensory/quality benefits* of CM, and finally, measured actual liking and some basic sensory-quality measurements in response to evaluation of a placebo CM sample. In this case "placebo" means participants did not evaluate actual CM at any point in the study. Instead, cooked commercial beef burgers (patties) were served labeled as 'cultured' and 'conventional' in different sizes - 'cultured' burger was served as a smaller piece to indicate limited availability. Rolland et al. (18) found an initial positive perception of CM among participants who claimed to "know exactly what CM is" (p. 8). Participants who had never heard of CM or had heard of it but were unfamiliar with it experienced a greater increase in acceptance toward CM. The placebo sensory evaluation also increased consumer acceptance: after tasting the purported CM, a higher score in willingness to taste CM was observed, participants reported willingness to pay a premium price for CM (on average 37% higher price than conventional meat), and positive judgment on the taste of CM was observed.

Benjaminson et al. (7) reported the first successful attempt to grow CM in the form of goldfish tissue-explant "fish fillets." The resulting product was then cooked and evaluated for its aroma and appearance (but not taste) by 4 employees of the lab without sensory-evaluation training. Cultured fish was reported to be as easy to harvest and to react the same way when cooked as conventional fish filets would. From a sensory point of view, cultured-fish filets were reported to be glistening, firm, and odorless (7).

In the last several decades, direct tissue-explant methods for growing CM have been largely superseded by scaffold-based methods, which is reflected in the more recent sensory-evaluation studies [*N*=3; (53, 55, 58)]. Ong et al. (55) used jackfruit/textured soy-protein (TSP)-based scaffolds to grow pork cells. This method was shown able to mimic seared beef's shrinking and color-changing behavior (although, not seared pork's) which the authors implied to as an "indicat[ion of] its utility to mimic cooked meat" (p. 5). Ong et al. (55) conducted a between-subject, visual sensory evaluation, asking each of the 2 groups of participants to evaluate a picture of either TSP-scaffolded (*N*=38 untrained participants) or jackfruit/TSP-scaffolded (*N*=40 untrained participants) cultured pork. Based on consumer evaluation of pictures of the grown cultured pork, the meat-like mimicry of the jackfruit/TSP significantly scaffold improved participants' perception of CM products by more than 8% compared to the TSP-based scaffold (55).

Lee et al. (58) also investigated the effects of novel scaffold on sensory-relevant characteristics of CM products. The authors created a TVP/fish gelatin-based scaffold and grew mouse cells as their CM model. Lee et al. (58) then instrumentally analyzed for color (colorimeter), texture (texture profile analysis in comparison to multiple beef brisket, chuck, and tenderloin), flavor (GC–MS), and taste (electronic tongue). The authors described their product as having a similar texture to a beef tenderloin, although the product was based on mouse cells. Flavor analysis of the cooked product confirmed the presence of common Maillard-browning produced aroma compounds, namely acetophenone, 2-ethyl-1-hexanol, nonanal, octanal, and nonanol (58), although it is important to note that these compounds are not the only or even the most characteristic products of Maillard browning, and that Maillard browning can occur whenever proteins and sugars are heated together, not only in meat products (60). Moreover, the listed compounds were not determinants of meat sensory characteristics as most key meaty aroma compounds from Maillard reaction are heterocyclic (61, 62). Taste analysis showed that

TABLE 6 Summary of product evaluation of meat products in the included studies (*N* = 5 studies).

Papers Reference	Product	Sensory evaluation method	Key findings
Rolland et al. (18)	Commercial beef burgers	• A wanting/ liking test was conducted on identical commercial beef burgers. • Samples were presented to panelists as 'conventional' and 'cultured'. • 'Cultured' hamburgers were served in a smaller portion than 'conventional'. • Participants (N = 193) rated the hamburgers' appearance, color, smell, tenderness, and juiciness.	• High acceptance of cultured meat among panelists when the known information about cultured meat is positive and supported by a favorable tasting experience. • Overall, participants perceived cultured meat as safe and appropriate food.
Benjamison et al. (7)	Cultured goldfish	• Fried fish filets were evaluated for aroma and appearance by 4 panelists.	• Cultured fish reacted to the cooking process as would fresh fish. • Panelists perceived the product acceptable as food despite the absence of tasting.
Ong et al. (55)	Cultured pork [porcine myoblast on texturized soy protein (TSP) and jack fruit-containing scaffold (JFS)]	• A single-blind test was conducted on a photo of (created) cultured pork grown on JFS or TSP scaffold • Participants (N = 78 university students) rated their attitudes toward the product.	• Pan fried JFS-cultured pork showed meat-like browning behavior and potentially shelf-stable meat-like color. • The use of JFS improved participants' perception of the product by more than 8%.
Lee et al. (58)	Fish gelatin/ agar (GA)-coated textured vegetable protein (TVP) scaffold with mouse blast as model meat cells	• Scaffolds made of TVP, GA-coated TVP, and a GA-coated TVP with mouse myoblast were compared to commercial beef cuts (chuck, tenderloin, and brisket) for texture, flavor, and taste. • Evaluations were done using analytical instruments.	• Cultured meat's texture, flavor, and taste implied as comparable to that of slaughtered meat due to the synergistic effect between the myoblast and scaffold.
Pasitka et al. (53)	Cultured chicken (Mixed-breed chicken cultured adipocyte-like cells combined with extruded soy protein)	• Panel 1: cultured chicken was served as a meal and rated for overall impression, flavor, texture, aroma, and overall experience of the product (N = 13 participants). • Panel 2: cultured chicken tasted alongside soy-based chicken and rated for their texture and flavor in a blinded-test (N = 30 participants). • Panel 3: cultured and soy-based chicken in comparison to farm-raised chicken breast. Participants (N = 13) were asked to rate the general flavor, texture, aroma, and overall experience.	• Overall, participants found the cultured chicken dish acceptable (average likelihood of 8/10 to replace farm-raised chicken with cultured chicken). • Sixty seven percent of the blind-tasting participants preferred cultured chicken over the soy-based alternative.

compared to a beef-brisket sample, the cultured mouse sample had similar (predicted) bitterness with lower sourness and higher umami values. The perceived aftertastes ["the taste that remains on the tongue after completely swallowing the food"; (58), p. 38242], namely astringency, bitterness, and umami were similar to the tested beef-brisket.

The only study that conducted sensory evaluation with human subjects that involved actual tasting of a real CM product was published very recently by Pasitka et al. (53). Sensory evaluation by untrained panelists was conducted in 3 different studies which evaluated overall sensory characteristics of a hybrid plant-protein/cell-cultivated chicken product (*N* = 13 participants), a preference test comparing this hybrid-CM product against a soy-based chicken (*N* = 30 participants), and a preference test comparing the hybrid-CM, the soy-based chicken, and conventional chicken (*N* = 13 participants). Based on the (forced-choice) preference test, most participants (67% of 30 participants) favored cultured chicken over soy-based chicken in terms of sensory attributes. In the first sensory evaluation, when participants (*N* = 13) were asked "how likely are you to replace your meat choice with this (cultured chicken) product?" [(53), p. 41], "the average likelihood stated by participants was 8/10" [(53), p. 41]. The cultured chicken also showed remarkable similarities to conventional chicken in sensory attributes, including taste.

4 Discussion

The studies identified for this review were almost entirely affective consumer studies, with no analytical sensory evaluations (63). Although the eligibility criteria were not designed to identify solely affective studies (see section 2.2), the prevalence of affective studies speaks to the relation between products' sensory characteristics and consumers' decision-making when it comes to any food. This can be further explained by considering the complimentary relationship between sensory science and consumer science in the analysis of "product micro lifecycle" from product purchase to consumption (64).

Consumer science focuses on explaining consumers' choice based on psychological stimuli such as product information and past experiences while sensory science explains consumption based on psychophysics—a combination of physical stimuli and human perception (64). Therefore, understanding the concept and actual identity of CM is necessary.

4.1 Sensory perception based on imagined or expected products

The main discussion in this section revolves around the CM sensory characteristics claim and consumer acceptance based on evaluation of CM as an idea (positive information framing), not an actual product evaluation. As shown in the results (section 3.3.1), a majority of studies' respondents had negative expectations of CM as an imagined product, and particularly of its sensory qualities. Novel-product unfamiliarity was hypothesized as the main reason for consumer skepticism toward CM. For example, according to Weinrich et al. (65), pre-knowledge of a product was a mediator between one's demographic background and attitudes toward the product. On a similar note, Lin-Hi et al. (66) considered CM as a "radical innovation in food sector" - an innovation that radically breaks with familiar logic and habits - which they hypothesized explained the tendencies for consumers' skepticism toward this product. The implication is that this skepticism manifested in multiple ways including perceptions of disgust (67), and perceptions that CM is more unsafe and unnatural, leading to further rejection of new food products (33, 67–70).

In order to determine whether unfamiliarity, skepticism, or neophobia might drive negative expectations around CM, information framing was used in many of these studies to determine if different frames increased acceptance. Various positive framings from labeling to the use of 'placebo' products were conducted and, overall, these all tended to improve expected consumer acceptance toward the product when properly directed (section 3.3.1). Positive framing focused on aspects such as product safety, health benefits, and environmental sustainability was found to increase consumer acceptance. This aligned with suggestions from many studies to highlight the key drivers of consumer acceptance namely safety and health benefits as well as showing that CM is a natural product that resembles conventional meat (18, 71–73). These framing approaches to increasing acceptance may be necessary as some studies reported that while some consumers (initially) were willing to support CM because of the benefits to animal welfare and the environment (65, 70), many consumers are not actually aware of these adverse environmental and animal-welfare impacts of the conventional system of producing meat. Therefore, in many studies these frames may be simultaneously informing consumers of a problem and providing CM as a solution (13, 74).

It is important to note that all 26 studies reviewed framed CM positively, regardless of the specific frame. The selection criteria for the scoping review were not designed to select papers with a particular position on this sometimes-controversial biotechnology (75), so this result is itself noteworthy. Since many of the study authors are apparently invested in the potential of CM as a meat-production method, this preponderance of positive framing may not have been the *explicit* intention of authors of the reviewed studies, either. However, since there have apparently been no sensory- or consumer-evaluation papers that investigated the effect of a *negative* framing on CM, this may be a source of bias in the literature, particularly confirmation bias.

As reported by Ryynänen and Toivanen [(22); see also (76)], based on their exploration of the role of written and online media in framing and presenting CM, most articles highlighted only benefits of CM, and presented the only challenges for CM as the current high cost of production and the possible imperfect reproduction of the sensory characteristics of conventional meat. This absence of real critical framing may create a critical knowledge gap, since CM cannot truly be said to be risk-free. For example, based on their intensive review, Bhat et al. (4) predict CM to be more likely to have a substrate contamination risk from the growth media, in contrast to the bacterial contamination from processing that is a problem for conventional meat. An overview by Broucke et al. (77) claims that the "addition of compounds and solutions like sera, growth-hormone factors (GHF), (bovine serum) albumin (BSA), and transferrin, withhold an additional risk due to possible introduction of harmful or pathogenic agents, especially in the case of *in vivo* gained animal sera (mostly fetal, but also new-born or adult source). Examples of possible contamination are prions, bacteria (including mycoplasma), and viruses (e.g., hepatitis virus)" (p. 7). Risks may also arise within the cell-handling and -cultivation process; not only additional contamination, but also potential genetic drift that can cause unintentional genome alteration of the cultured cells (78). Furthermore, it is possible for adult stem cells to become malignant in long-term culture (79). The effect of these more negative counter-narratives on consumer acceptance have yet to be explored, thus it may be premature to conclude that only positive framing has an effect on consumer willingness to buy/eat CM and their perceptions of its quality.

4.2 Sensory characteristics based on actual product evaluation

Despite the many promises and the insistence in the literature that CM will have sensory characteristics equivalent to conventional meat (18, 80, 81), there was very limited evidence of the actual sensory characteristics of CM. In this review, (meat) product evaluation was only found in 5 studies, with 1 conducted on a "placebo" consisting solely of conventional meat, and 4 on CM (see section 3.3.2). Overall, these studies did conclude that the evaluated CM closely resembled its conventional counterpart in both sensory characteristics and reaction to cooking. These studies speak to the potential for CM products to ultimately resemble their conventional equivalents.

However, the claim that CM products will always have, or even currently have, the same sensory characteristics as conventional meat products is not well-established in this current literature. Three main issues are as follows: (1) only one study reports an actual sensory evaluation with tasting of CM products; (2) in all studies excepting Rolland et al. (18) (which did not actually involve CM products), evaluations were conducted with unacceptably low numbers of human panelists (this standard is described with more detail in section 4.2.2); and (3) the CM products evaluated were not comparable to their target, conventional equivalents.

4.2.1 Lack of product tasting

Almost all studies did not involve actual tasting of a product, CM or otherwise. Lee et al. (58), Pasitka et al. (53), and Rolland et al. (18) stood out among the actual sensory evaluations for reporting details about taste and flavor in CM products (see section 3.3.2). Among these three studies, only the placebo panel by Rolland et al. (18) and the CM sensory evaluation by Pasitka et al. (53) included actual human-subject evaluation by taste of any product.

The result of the Rolland et al. (18) placebo panel (section 3.3.2) was considered a notable success in the acceptance of CM products, not only by the authors, but also by many others who have cited these results as proof that consumers will accept CM (59, 68, 82, 83). Compared to a past consumer liking test investigating novel food technologies by Tan et al. (84)—participants were served novel foods such as lamb brain, frog meat, or meal-worms burger and rated the products as inappropriate for food—Rolland et al. (18) results with a sensory panel evaluating placebo products found that 'cultured' hamburger was considered to taste slightly better than 'conventional', and to therefore be acceptable as a substitute. The authors also noted that among the 4 acceptance questions they used, "…the willingness to taste cultured meat had a much higher score than the responses to the other questions" [(18), p. 13]. Interpreting this statement, the authors hypothesize "[a]s perceived danger is a major determinant for willingness to taste novel foods [26], this suggests that participants did not consider cultured meat dangerous" [(18), p. 13]. Thus, "…a cultured meat hamburger is considered an appropriate food [by participants] when its sensory features are equivalent to conventional meat" [(18), p. 13].

Looking closely at the context of the Rolland et al. (18) study, however, these results are scarcely indicative of consumers' acceptance of CM. Rather than perceiving CM as safe to eat, the high willingness to taste CM score could as plausibly be interpreted to reflect participants' curiosity about the product, considering it was not yet at all available in the market, and the notoriety of some of the study's authors, who were responsible for the first televised tasting of CM hamburger (85, 86). Since the study was *in vitro* it also does not establish whether consumers would be willing to continue consuming the product (87, 88). Furthermore, it should be emphasized, as conventional hamburger was the only sample presented in this study to taste, this study did not prove anything about the sensory characteristics or acceptability of CM; instead, it showed how much participants like the taste of conventional meat. The results are only generalizable to CM if it does indeed have exactly the same sensory characteristics of conventional, beef hamburger.

The study by Lee et al. (58), although included in our review because of the detailed attention to sensory characteristics of its CM sample, did not use human senses to evaluate the product. Instead, they use instrumental analyses to *predict* flavor, taste, and texture characteristics. Although created to model a human tongue, the sensor performance of an electric tongue differs with respect to sensitivity, selectivity, and detection limit for the compounds of interest (89). Regarding flavor as measured by volatile aroma compounds, the absence of furans, pyrazines, oxazoles, and other essential sulfur-containing flavor compounds in the final product are concerning, and may indicate that the CM will not have a flavor equivalent to conventional meat, since these are key aroma compounds for red meats (58, 90, 91). In the absence of any human sensory evaluation, these results should not be treated as indicative of the "true" sensory experience of CM.

The hybrid (plant and cell based) chicken product evaluated in the study by Pasitka et al. (53) is currently the only CM product currently reported in the literature to have undergone sensory evaluation for flavor by human subjects.

4.2.2 Low power sensory studies

Sensory evaluation focuses on person-product interaction; it requires an interaction between a person and a stimulus (63). Colloquially, sensory evaluation uses human subjects as "instruments" to determine the analytical or affective characteristics of a (food) product. Typically, sensory evaluation methods are broken down into three broad categories: discrimination tests ("are their perceptible differences among samples?"; require trained or untrained panelists), descriptive tests ("what are the perceived sensory differences among the samples?"; require trained panelists), and affective/hedonic tests ("how are these samples liked by different subjects?"; require untrained panelists) testing.

Among the included studies, the studies by Benjaminson et al. (7) and Pasitka et al. (53) were the only ones to involve direct person-to-CM evaluation. It is important to recall that Benjaminson et al. (7) did not allow subjects to taste the samples. Both studies based their results on a number of subjects that would be universally considered too low for statistical power by the standards of sensory science (see section 3.3.2). Both studies did not specify the specific objective(s) or research questions that were addressed by conducting sensory evaluation, but based on their results, the authors seemed interested in identifying similarities between their CM and its conventional counterpart as well as proving its acceptability among consumers. The recommended number of panelist in an affective study depends on several factors, including the expected quantitative differences among products, the specific research question, the method of collecting data, the desired population to which the results should generalize, and the complexity of the products themselves (92). To achieve a proper predictive validity, it is typically recommended to have 24–40 panelists for a simple difference test and 50–100 consumers for a hedonic test without post-hoc segmentation (63, 92, 93). Unfortunately, Benjaminson ($N=4$ panelists) and Pasitka ($N \leq 30$ panelists, depending on sub-study) simply did not include sufficient panelists in their studies.

Furthermore, within an affective test, Pasitka et al. (53) asked their untrained panelists to measure specific sensory attributes such as sweetness, savoriness, saltiness, aftertastes, chicken flavor, and other attributes (Table 6). This type of sensory-evaluation test should be done through descriptive sensory methods, which require 8–12 well-trained panelists: individuals that have been trained to evaluate reference standards and reach an objective, within-group consensus about the meaning of terms like "chicken flavor" (63). The statistical power of descriptive methods even with such a small number of panelists is typically justified by the reduction of variance through this calibration (training). Furthermore, recent research has shown that even "simple" terms like sweetness are not suitable for evaluation by untrained panelists (94). Thus, the conclusions about specific sensory attributes based on very small, untrained panels as in the study by Pasitka et al. (53) are unlikely to be reliable.

4.2.3 Non-equivalent sample evaluation

Of the few studies that actually produced CM samples for evaluation, two studies evaluated samples that do not correspond to meat that people usually consume, namely cultured goldfish and cultured mouse. The creation of a goldfish filet by Benjaminson et al. (7) was the first success story for the creation of cultured fish. Although the process was not yet practical from a yield standpoint at that time, the authors stated that they had successfully "... addressed fundamental *in vitro* skeletal muscle growth parameters" and that "… the yield versus cost calculation projects a favorable outcome provided sufficient research effort and resources become available" [(7), p. 887]. Of course, humans do not typically consume goldfish, so this work on a model species was meant to be a stepping-stone toward the production of CM fish from actual food species. It is not unreasonable to observe that this study was published more than two decades ago; by now other labs working on cultured fish should surely have been able to improve on or at least replicate results of Benjaminson et al. (7). Unfortunately, this optimism does not seem to have been realized; not only is cultured fish not in the market as of this time of writing, but no further record of evaluation on cultured fish product(s) has been published for inclusion in this review.

The creation of CM that mimics the texture of beef tenderloins is certainly worthy of note (58). However, there is not yet evidence that this approach can succeed using cells from animal species that are more commonly consumed than mice. This consideration is not merely a quibble, considering the different genomic resources between species which confine cell differentiation to result in tissues that are species-specific (95, 96). Thus, being able to produce 'cultured beef tenderloin' from mouse cells does not guarantee that this approach will be successful for the creation of products with, for example, cow cells.

4.3 Realities of CM production

The majority of papers included in this review ($N = 24$ studies) present CM as an entirely positive, transformational biotechnology. This is emphasized especially in studies that communicated these concepts to participants as framing ($N = 18$ studies). In framing studies, participants are asked to believe that the given, invariably positive frame about CM is an unproblematic truth. These frames are typically consumer-appropriate versions of the arguments given in support of CM as a technology in the literature ($N = 18$ studies; examples in Table 5 in "positive framing"). However, as reported in an increasing number of studies, these arguments in favor of CM are exactly that—arguments, not inevitable truths (77, 88). Predicting the future development of CM as both a process for producing a food and as a consumer product has turned out to be considerably more complicated.

Typically, arguments in the papers reviewed here imply that CM is isomorphic with conventional meat but produced in a more sustainable way. However, as long as CM has continued to be a hypothetical product, this claim has not been supported by enough evidence. CM typically is argued to be more sustainable because it would cause less environmental damage—requiring fewer natural resources and less land use, and causing lower greenhouse-effect gas-emission—than conventional forms of livestock production for meat (2, 4, 6). However, those statements are typically based on theoretical projections with large uncertainties (97, 98). In addition, although *in vitro* CM production may require lower agricultural inputs, including land use, it would require more intensive energy use in return. Lynch and Pierrehumbert (99) also reported that, although cattle farming has grater peak (global) warming effect, the warming effect would not persist nor accumulate under reduced 'farming' system as would *in vitro* meat production. While CM production's benefits in terms of sustainability are likely to be much more complex and contingent, the papers reviewed here presented CM production only in terms of maximal, unalloyed benefits, both in argumentation ($N = 24$ studies) and in experimental design ($N = 18$ studies).

As for CM being exactly the same as 'real meat', the burger grown in Professor Mark Post's laboratory and presented in 2013 has been, to this date, the only consumed 'pure (cultured) meat' in real life. According to the three tasters, "…the burger was dry and a bit lacking in flavor" (85) in which one of them described "the bite [texture] feels like a "conventional hamburger" but that the meat tasted "like an animal-protein cake."" (85). The recently sold cultured chicken and fish products are a hybrid of animal cells and plant-based materials (100). This reality is reflected in this review; the only CM product that was evaluated by taste was a hybrid product of soy protein and chicken cells and not *just* 'animal meat' (53) as is typically presented in the framing and narratives documented in these studies.

Beyond the challenge of developing a CM product that can be an acceptable sensory substitute for conventional meat, high production costs have remained a hurdle. Proponents of CM have claimed that Moore's law - formulated for microprocessors, and arguing that the cost of production of novel products will always reduce exponentially over time - would apply to CM (88). Moore's law has, however, not typically been applied to biological systems, which are the basis of CM production, due to the complexity and unpredictability of biological events and the mechanisms behind it (88). Ten years ago, a five ounce burger costed over $300,000 to make (85, 101) and so far, CM products have been sold for about $18 per meal—a loss regarding which producers were not willing to share further details on (102). Thus far, reframing CM as a plant/animal-cell hybrid product seems to be more realistic both from a product-formulation and a production-cost point of view. Using cell cultures as flavorings of a plant-based meat is what most CM producers are moving toward (102). The future of CM has once again been proven unpredictable, suggesting the importance of sober and realistic interpretation of the literature in order to avoid bias and overexcitement.

Other than to further understand potential consumer attitudes toward CM, many consumer acceptance studies were directed to ensure the *increase* in consumer acceptance of CM (34–36). For example, after determining drivers for consumer acceptance and rejection of CM, the authors suggested ways to market CM such as framing CM as a solution to the existing food safety problems (68) and portraying CM as more natural, favorable, and addressed consumer concerns about the technology could improve consumer perceptions of the product (70). A similar pattern was also found in more recent publications (66, 72). This indicated that increasing consumer acceptance is the main interest of CM proponents which could be a critical source of bias throughout literature in this area.

4.4 Researcher investment in CM as an idea

The intense promotion of CM as a world-changing biotechnology makes research around this topic prone to bias. To investigate this, conflict of interest statements, study supports (source of funding, panelist, and samples), and authors affiliations were examined (Appendix 5). Based on the results, the panelists and sample sources were unlikely to be a source for bias/conflict of interest. This was because the studies used random participants from a crowd sourcing website, conducted national/cross-country survey, or obtained random internal participants such as college students. Only the study by Benjaminson et al. (7) acknowledged using panelists who were their own lab members. As for sample sources, almost all studies that conducted a sensory panel made their own sample. Only one study bought commercial samples [hamburger; (18)]. Further details can be seen in the Supplementary material.

Possible sources of bias were sought in the conflict of interest statement, author affiliations, and funding sources (Appendix 5). Eight of the included studies did not include a conflict of interest statement while most studies ($N=17$) declared no conflict of interest. Ong et al. (55) was the only study that declared potential conflict of interest. Ong et al. (55) declared that portions of the reported research has been submitted for a patent (patent application no. PCT/SG2020/050432) to two of their authors, Shujian Ong and Hanry Yu. Furthermore, both Shujian Ong and Hanry Yu were affiliated with Ants Innovate Pte Ltd., a Singapore deep tech start-up that focuses on developing cultivated whole meat cuts. Studies' funding sources showed that many included studies were funded through a government grant and/or internal funding ($N=12$ studies), from independent-nonprofit organizations ($N=12$), and from the CM industry ($N=2$ studies). Upon examining the authors' affiliations, almost all authors were university affiliates, with only a few independent or industry researchers ($N=3$ studies). These 3 studies included at least an author that is affiliated with a CM industry: Ants Innovate Pte Ltd., Believer Meats, and Mosa Meat (Appendix 5).

While the development of cultured meat is happening across public research labs and private industry, most of the reported success in producing CM products is in private industries such as Upside foods, Good Meat Inc., Scifi foods, and Blue Nalu (100, 103). With CM formulation becoming companies' best-kept secret, perhaps for this reason the real sensory characteristics of CM are still unreported in the scientific literature. In this review, CM products that were evaluated were all made in-house by the research teams. This implies that CM products produced by industry were not made available for independent assessments. If CM is only developed by a handful of individuals that are likely proponents of this product, implicit bias of reporting positive results is very likely to take place; it is very unlikely that negative results will be published at all. In fact, the known consumer related studies and information given to the media are mostly the success stories of CM development (22, 76).

5 Limitations

This scoping review focused on identifying proof of the sensory characteristics of cell-cultured meat (CM), not to identify the consumers' responses toward CM or judging the product of CM. Thus, the results should be interpreted within this context, not necessarily in terms of the larger feasibility of making high-quality CM acceptable to consumers or even the possible *future* sensory characteristics of CM products.

In terms of data collection, this scoping review was restricted to publications in three agriculture-based databases. Considering the extremely active nature of publications around the topic of CM, it is likely that some manuscripts are not retrieved from our initial search. For example, while studies by Chriki et al. (104) and Liu et al. (105) were not captured by our search strategy, they were brought to our attention after article submission. While these articles would not significantly change our conclusions about the state of the field—both asked consumers to hypothesize about how "tasty" cultured meat would be—they are an example of the active and rapid state of the discourse. A different result might be obtained if more than three databases were included or done in multidisciplinary databases (e.g., sociology, psychology, and communications) or related disciplines such as engineering. Furthermore, the review was restricted to publications written in English language. This means that the findings may not reflect the body of literature in other languages. The scoping review was designed to include the sensory characteristics of CM in general which was reflected in the absence of use of specific meat terms (e.g., "cultured seafood," "cultured chicken") in the search strategy. Thus, the results of this review should not be used to indicate a very specific type of CM.

As for the review method, the citation chasing approach could be improved. Instead of only backward citation chasing, a more thorough citation chasing could be done which includes checking all references in the included articles. Finally, data extraction was conducted by only one author with a second author as a reviewer (spot checking); although a valid approach, having more expert opinion in the process would further reduce the chances of misinterpretation.

6 Conclusion

Cell-cultured meat (CM) has been widely introduced as *meat produced in a more sustainable way*, implying it is better for the environment and will have the same sensory characteristics of conventional meat. Using structured, best-practice, scoping-review methods, the current state of knowledge regarding CM's sensory characteristics was surveyed, with a focus on both the directly known attributes and the methods used to identify those attributes in the literature.

In the literature CM sensory-attribute characterization was performed regardless of product availability where a majority ($N=19$ studies) of the included studies use positive framing to provoke stated preferences of CM among consumers and only a few ($N=5$) studies conducted anything that could be characterized as an actual product evaluation. All reviewed studies demonstrated some possible weaknesses for drawing certain conclusions about the sensory characteristics of CM, namely: not actually tasting CM, low statistical power, or evaluation of unrealistic CM samples. Therefore, we must conclude that there simply is not currently evidence of the strong claim found throughout the larger literature that CM will have the same sensory characteristics as conventionally produced meat products. What the large minority of the included studies did show were possibilities to create cell-cultured products (CM) that mimic the color, texture, and response to cooking (color change and shrinking) of their conventional counterparts.

In conclusion, with the strong flux of advancements and reformulations currently ongoing around CM production, the sensory characteristics of cultured meat remain a mystery. Based on what is known, it is fair to state that CM still has a long way to go before achieving the exact sensory characteristics of the conventional meat that is in the market today. Based on the reviewed studies, it seems that the future of CM may be a hybrid product of cultured animal cells and plant proteins, which may achieve desirable sensory characteristics but will almost certainly not be exactly equivalent in sensory characteristics to conventional meat. Outside of the primary focus of this review it was observed that recent developments in CM are reported more in the mass media than in the peer-reviewed literature. Thus, media studies, communications studies, and sociological research in this area could contribute to clarifying what is expected and known about the actual sensory characteristics of CM. For the moment, from this review it is only possible to conclude that CM may someday succeed in producing a product with desirable and meat-like sensory characteristics; the guarantees and claims currently being made are not well-based in the peer-reviewed literature.

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

KT: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing, Investigation. CC: Conceptualization, Methodology, Writing – review & editing. SO'K: Writing – review & editing. JL: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing, Resources, Writing – original draft.

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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

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2024.1332765/full#supplementary-material

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Oat-based milk alternatives: the influence of physical and chemical properties on the sensory profile

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Introduction: Oat-based milk alternatives (OMAs) have become increasingly popular, perhaps due to their low allergenicity and preferred sensory attributes when compared to other milk alternatives. They may also provide health benefits from unique compounds; avenanthramides, avenacosides, and the dietary fibre beta-glucan. This has led to a variety of commercial options becoming available. Being a fairly new product, in comparison to other plant-based milk alternatives (PBMAs), means little research has been undertaken on the sensory profile, and how it is influenced by the physical and chemical properties.

Methods: This study investigated the sensory, physical and chemical profiles of current commercially available OMAs, that varied in fortification, use of stabilisers, and oat content. The volatile compounds and their respective aromas were analysed using solid phase microextraction followed by gas chromatography mass spectrometry (GC-MS) and gas chromatography—olfactometry (GC-O). Liquid chromatography mass spectrometry (LC-MS) was used for identification of avenanthramides and avenacosides. Particle size and polydispersity index (PDI) were analysed using a Mastersizer and Zetasizer, respectively, with colour analysis carried out using a colourimeter, and viscosity measurements using a rheometer. Descriptive sensory profiling was used to assess the impact on the sensory characteristics of the different samples and the sensory data acquired were correlated with the instrumental data.

Results: Samples with smaller particle size appeared whiter–both instrumentally and perceptually. The only clear plastic packaged product differed substantially in volatile profile from all other products, with a higher abundance of many volatile compounds, and high overall perceived aroma. Avenanthramides and avenacosides were present in all samples, but differed significantly in abundance between them.

Discussion: The results suggested smaller particle size leads to whiter colour, whilst differences in processing and packaging may contribute to significant differences in aroma. Astringency did not differ significantly between samples, suggesting that the variation in the concentrations of avenacosides and avenanthramides were below noticeable differences.

KEYWORDS

oat, milk alternatives, sensory, physico-chemical, avenanthramides, GC-MS, particle size, LC-MS

1 Introduction

Plant based milk alternatives (PBMAs) have substantially increased in popularity, now accounting for around 8% of total retail "milk" sales in the UK (1). A shift away from cow's milk may be due allergies and intolerances (2), and concerns over climate change, land and water use (3). Oat milk alternatives (OMAs) have received particular interest due to unique potential health benefits (2), including the presence of beta glucans — a dietary fibre shown to be beneficial in preventing diabetes, as well as lowering total blood cholesterol, and reducing the risk of cardiovascular diseases (4, 5). An increase in nut allergies (6) and soy allergies (7) make oat a popular alternative to other PBMAs. Oats also contain unique compounds with antioxidant properties, including avenanthramides (8), a group of phenolic compounds unique to oats, which have been shown to have anti-inflammatory effects (9), and avenacosides, which exhibit antifungal properties (10).

However, OMAs may face nutritional, sensory, and physicochemical challenges. The qualities of oat milk have not yet been fully investigated in comparison to other PBMAs such as soya, which has been on the market for over 70 years and for which there is extensive available research and literature (7). Despite being designed to have similar sensory properties to cow's milk, some consumers find the difference in attributes to be unacceptable (11) whilst the nutritional value tends to be low in comparison to bovine milk (12).

The full production process of oats to OMAs is described by Zhang et al. (13) to include the following steps: dehulling groats, flaking, wet milling, enzyme hydrolyses, decanting, followed by additional ingredient formulation, ultra-heat treatment (UHT), and finally storage. However, with a variety of commercial OMAs available, it is possible these production steps may vary considerably, leading to varying sensory, and physicochemical properties. Processing can lead to a loss of vitamins and minerals (14), with a shorter UHT holding time enabling beverages to retain a higher level of vitamins during storage (13). Processing methods may also modify the physicochemical characteristics of beta glucans, with these effects being highly process-dependant and difficult to predict (15). Some differences may be due to drivers in industry, with some producers driven more by flavour cues focussing on how the product looks, acts and tastes, some influenced by concern over environmental or health claims, and others by nutrition (1).

The appearance of OMAs has been shown to have a significantly lower whiteness index than cow's milk, making them easily distinguishable (7). A slight brownish colour may be due to natural pigments, and colour differences could result from differences in size and concentration of particles (16). Colour analyses on milks has shown those with lower particle size have a higher lightness index than those with larger particle size, as a result of light scattering (17). This may lead to an "off-white" colour some consumers could find unappealing (16). Bovine milk and soy milk contain only a small fraction of large particles, whilst oat milk has been shown to have twice as many large particles (>3 μm) as small particles (<3 μm) (18). Stability may affected by the polydisperse distribution of particles in OMAs, leading to an increased separation rate, with high amounts of sedimentation and creaming (7). Particle size has also been found to be highly correlated with stability in milks — with more stable milks measuring smaller particles (18). The high concentration of starch in OMAs can lead to increased viscosity (2), whilst the fortification of PBMAs may lead to chemical instability of the nutrients and nutraceuticals added (11).

Off-flavours in OMAs may result from the presence of unsaturated fatty acids and lipoxygenases that can lead to the formation of n-hexanal and n-hexanol, which are associated with a "beany" or "off" flavour (2). Production and storage can lead to lipid degradation and oxidation, causing the development of these off-notes (13). This may be problematic, as hexanal is considered a rancidity marker and may affect the acceptability of OMAs (19). In order to provide sensory attributes similar to those of cow's milk, many OMAs contain stabilisers, emulsifiers, and flavourings (1).

The phenolic compounds in oats, including the previously mentioned avenanthramides, may also affect the sensory properties, as these have been found to correlate with bitter and astringent sensations (20). Astringent compounds can react with salivary proteins, leading to a loss of lubricity and result in a rough-tactile feeling in the mouth (21). However, it still remains to be established as to whether the phenolic compounds in OMAs are present in sufficient quantities to be perceived as astringent. Research has also shown that these phytate and oxalates present in oats may have anti-nutritional effects, reducing absorption of minerals (22). Cow's milk naturally provides a variety of minerals including calcium, as well as vitamins B_2, B_{12}, A, and E, therefore OMA's may be fortified to closer match this (11). However, mineral fortification may be undermined if absorption of the added minerals is hindered by phenolics, phytate and oxalates. Cow's milk also contains proteins with all of the essential amino acids required by humans, being highly digestible and bioavailable (23), whereas OMAs are generally low in protein in comparison (12), with just

TABLE 1 Stated ingredients for the six products used in this study collected from online sources and/or product packaging at time of purchase.

Sample	Ingredients	Packaging	Shelf life
A	Oat base (water, oats 10%), rapeseed oil, calcium carbonate, calcium phosphates, salt, vitamins (D2, riboflavin, B12), potassium iodide	Liquid carton packaging (paperboard)	Long life
B	Oats (15%), water, rapeseed oil, salt	Liquid carton packaging (paperboard)	Long life
C	Oats 9%, oat flour 1%, plant fibre from citrus, water, salt	Clear plastic	Short
D	Oat base [water, oat (9.8%)], chicory root fibre, sunflower oil, calcium (tri-calcium phosphate), sea salt, stabiliser (gellan gum), vitamins (B2, B12, D2)	Liquid carton packaging (paperboard)	Long life
E	Water, oats (10%), rapeseed oil, tricalcium phosphate, calcium carbonate, salt	Liquid carton packaging (paperboard)	Long life
F	Spring water, organic gluten-free oats (11%), organic cold-pressed sunflower oil, sea salt	Liquid carton packaging (paperboard)	Long life

0.4–1% protein content (24). The protein in oats is also limited in the amino acid lysine, and may have poor digestibility (25).

Differences in the physicochemical, and volatile profiles may affect the taste, appearance, mouthfeel, and functionality of products. The sensory profile may be affected by astringency, resulting from avenanthramides and avenacosides, whilst differences in processing and packaging may possibly lead to off-notes. It is also possible that particle size and polydispersity index may lead to differences in stability and appearance. These differences found in individual products may affect overall acceptability of OMAs. Therefore, this paper focuses on the sensory, physicochemical and volatile profile of existing OMAs, and explores how these relate to one another. The aim is to identify specific compounds and properties in OMA's and investigate how they contribute to the sensory profile. With such information it is anticipated that future developments in formulation and process optimisation may lead to an improved sensory profile of OMAs and increase consumer acceptability.

2 Materials and methods

2.1 Materials

2.1.1 Oat milk alternatives

Six different OMA products were used for analyses, labelled; A, B, C, D, E, and F. These were standard commercial products from the UK market and selected based on the commercial availability, with factors such as price, accessibility and popularity taken into consideration, in order to accurately reflect a range of standard products for the industry. The selected samples had varying levels of fortification (Table 1) in order to analyse the potential effect of this fortification on resulting sensory attributes. The nutritional composition of the samples also varied, as shown in Table 2. All products selected were original versions—avoiding "barista," flavoured, or sugar-free alternatives, to ensure comparable products were assessed. All samples were UHT long shelf-life products packed in paperboard carton packaging, aside from sample C which was packaged in clear plastic, stored refrigerated and had a shorter shelf life. During this study commercial production of product C ceased, however, analysis of this product was completed as the substantial differences between this and other products were of interest. Samples from the same batch code were used for each sample for the sensory and flavour analyses, with the samples opened and analysed within the same day for the sensory panel and GC-MS analyses. Mastersizer, Zetasizer and colourimeter analyses were also carried out within 24 h of opening from the same batch codes. Samples were then frozen, to be thawed at a later date for GC-O, LC-MS, and rheological analyses. Each analytical method was carried out in replicates from 3 separate cartons to account for batch to batch variation.

2.1.2 Chemicals

For solid-phase microextraction (SPME), compounds used as standards were obtained from Sigma-Aldrich Co. Ltd. (Gillingham, UK): 1,2-dichlorobenzene (10 ppm in methanol) and the alkane standards C_6–C_{25} (100 µg/mL) in diethyl ester. Sodium chloride, and HPLC grade water, methanol and hexane, were obtained from Fisher Scientific UK. LC-MS grade formic acid (98–100%) and acetonitrile were purchased from Merck (Darmstadt, Germany). Standards avenanthramide A (i.e., 2p), avenanthramide B (i.e., 2f), and avenanthramide C (i.e., 2c), avenanthramide D phyproof®, and avenacoside A (>95%), were purchased from Sigma Aldrich Co. Ltd. (Gillingham, UK).

TABLE 2 Nutritional information of samples as stated on the product packaging at time of purchase.

Typical values	A	B	C	D	E	F
Energy (Kcal)	57	51	50	43	48	43
Fat (g)	2.8	1.5	0.8	1.5	2.1	1.6
Saturates (g)	0.3	0.3	0	0.1	0.2	0.4
Carbohydrate (g)	6.6	7.7	11	6.6	9.5	6.1
Sugars (g)	4.1	3.2	4.8	3.2	4.5	4.1
Fibre (g)	0.8		0	1.4		0.3
Protein (g)	1	1.3	0	0.3	0.2	0.8
Salt (g)	0.1	0.18	0.05	0.09	0.1	0.1
Vitamin B2 (mg)	0.21			0.21		
Vitamin B12 (µg)	0.38			0.38		
Vitamin D (µg)	1.1			0.75		
Potassium (mg)	151					
Calcium (mg)	120			120	120	
Iodine (µg)	22.5					

2.2 Sensory analysis

For the sensory analyses, descriptive sensory profiling was carried out over the course of 2 weeks, using the trained sensory panel at the Sensory Science Centre (University of Reading) comprising of eleven panellists. All panellists had a minimum of 6 months experience, as well as four specific sessions training (30-min each session) on the OMA's used during this study During week one, vocabulary development and training sessions contributed to the selection of thirty-five different attributes for scoring. To develop these attributes, coded samples were given to the panellists, and they were asked to describe appearance, aroma, taste, flavour, mouthfeel, and aftertaste/after-effects and produce as many descriptive terms as seemed appropriate. Reference materials (**Supplementary Table 1**) were used for assessors to confirm if the attribute was the appropriate descriptor. The vocabulary development and training sessions were carried out in a discussion room, whilst the quantitative sensory assessment took place in isolated sensory booths, each equipped with an iPad.

Once the consensus vocabulary was set, the panellists re-evaluated the OMAs and decided on anchors for the line scales. This led to an agreed profile of 8 appearance terms, 4 odour terms, 10 taste/flavour terms, 4 mouthfeel terms and 9 aftertaste/after-effects terms. Compusense Cloud Software (Compusense, Guelph, ON, Canada) was used to acquire the sensory data. The samples were provided in glass cups, with a saucer placed over the top—prepared approximately 5 min in advance of each sampling to create a headspace for aroma detection, tested at room temperature. The samples were randomly assigned two three-digit codes each (one for each of the two repeats) and given to the panel in a sequential balanced order. Over 3 days, the panel analysed each of the samples twice, and scored for each attribute using unstructured line scales (0–100). Panellists were instructed to sniff the samples first to score the aroma attributes, then assess the appearance before tasting (and swallowing) the samples to score the overall taste/flavour and mouthfeel attributes. There was a 30-s pause after the end of mouthfeel attributes and the panellists then scored the after-effects. Between samples, panellists cleansed their palate with water and crackers, with a 30-s pause between samples.

2.3 Instrumental analysis

2.3.1 Volatile compounds

2.3.1.1 Solid-phase microextraction followed by gas chromatography-mass spectrometry (SPME GC-MS)

Three millilitres of each sample were weighed into a SPME vial of 15 mL fitted with a screw cap and 0.5 g of sodium chloride was added along with 5 μL of 1,2-dichlorobenzene (10 ppm in methanol) as an internal standard. After equilibration at 40°C for 10 min, a 50/30 μm DVB/CAR/PDMS fibre was exposed to the headspace above the sample for 30 min. Four replicates from different product cartons were carried out over 3 days, in a randomised order each time. A blank run, using an empty carton, was used to ensure any volatile compounds from the lab or equipment were subtracted, as well as gain an indication of what compounds were present from the packaging. For this, a carton from Sample A was rinsed thoroughly and shaken with water, with 3 mL of this water analysed as a blank run. After extraction, the SPME fibre was inserted into the injection port of an Agilent 7890A-5975C gas chromatography mass spectrometer equipped with an automated injection system (CTC-CombiPAL). For the chromatographic separation, a capillary column HP-5MS (30 m × 0.25 mm × 0.25 μm film thickness) (Agilent, Santa Clara, CA, USA) was used. The oven temperature programme used was 2 min at 40°C isothermal and an increase 4°C/min to 250°C. Helium was used at 3 mL/min as carrier gas. The sample injection mode was splitless. Mass spectra were measured in electron ionisation mode with an ionisation energy of 70 eV, the scan range from 20 to 280 m/z and the scan rate of 5.3 scans/s. The data were recorded by HP G1034 Chemstation system. Volatile compounds were identified or tentatively identified by comparison of each mass spectrum with spectra from authentic compounds analysed in our laboratory, or from the NIST mass spectral database (26), or spectra published elsewhere. A spectral quality value of > 80 was used alongside linear retention index (LRI) to support the identification of compounds where no authentic standards were available. LRI was calculated for each volatile compound using the retention times of a homologous series of C_6–C_{25} *n*-alkanes and by comparing the LRI with those of authentic compounds analysed under similar conditions. The approximate quantification of volatile compounds was calculated from GC peak areas, by comparison with the peak area of the 1,2-dichlorobenzene standard, using a response factor of 1.

2.3.1.2 Solid-phase microextraction followed by gas chromatography-olfactometry (SPME GC-O)

After extraction (using the same optimal extraction conditions as used for GC-MS), the SPME fibre was inserted into the injection port of an Agilent 7890B series ODO 2 (SGE) GC-O system equipped with an HP-5MS column (30 m × 0.25 mm × 0.25 μm film thickness). The outlet was split between a flame ionisation detector and a sniffing port. The injector and detector temperatures were maintained at 280 and 250°C, respectively. The oven temperature programme used was 2 min at 40°C isothermal and an increase 4°C/min to 250°C. Helium was used at 2 mL/min as carrier gas. Three assessors with normal olfactory function, from the Department of Food and Nutritional Sciences, were trained and carried out the procedure. Each assessor evaluated by sniffing each sample in duplicate and documented the odour description, retention time, and odour intensity (OI) on a seven-point scale (2–8), where <3 = weak, 5 = medium, and >7 = strong. *n*-Alkanes C_6–C_{25} were analysed under the same conditions to obtain LRI values for comparison with the GC-MS data.

2.3.2 Avenanthramides and avenacosides

2.3.2.1 Sample preparation

The extraction was conducted according to Günther-Jordanland et al. (20), with some modifications to adapt from oats to oat-based milk. Each sample (10 mL) was placed into a separating funnel and 10 mL of hexane was added, shaken for 5 s and left to equilibrate for 15 min before removing the fat. The samples were then centrifuged at 4°C for 10 min at 9000 rpm, then the remaining hexane and fat layer was removed using a glass mini pipette. After this step, 500 μL of the sample was added to 1.5 mL of acetonitrile containing 50 μL of formic acid. This was then shaken for 1 h, centrifuged for 10 min at 9000 rpm, filtered using a 1.4 μm filter and analysed by LC-MS/MS. Each sample was analysed in triplicate.

2.3.2.2 LC-MS/MS analysis

An aliquot (1μL) of the prepared sample was injected into a UPLC-MS/MS QQQ system, LCMS 8050 (Shimadzu) combined with Luna Phenyl-Hexyl (150 mm × 2.0 mm inner diameter, 5 μm, Phenomenex, Aschaffenburg, Germany) equipped with a guard column of the same type. Eluent A was composed of 0.1% formic acid in water, and Eluent B was composed of 0.1% formic acid in acetonitrile. Using a flow rate of 300 μL/min, the system was operated at 25°C, starting with 32% B under isocratic conditions for 1 min, then increasing the content of B to 70% over 3 min, followed by an increase to 100% B over 2 min, and keeping isocratic conditions for 3 min. Eluent was pumped down again to 32% over 2 min and held isocratically for a further 3 min. Analysis was performed in ESI- mode using the following MRM transitions: avenanthramide A: 298 > 254.15 298 > 133.9 298 > 159.85, avenanthramide B: 327.8 > 284.25, 327.8 > 268.1, 327.8 > 160.85, avenanthramide C: 314 > 178.2, 314 > 134.85, 314 > 134.2, avenanthramide D: 282 > 238.2, 282 > 118.95, 282 > 144.85, avenacoside A: 1061.7 > 899.3, 1061.7 > 163. Dwell time was 10 ms for each transition and Q1, collision energy and Q3 voltages were optimised using standards of each compound.

The calibration curves were run with a linear curve fit, a weighting of 1/C^2, and were not forced through the origin. A quantitative method with external standards was used; avenanthramide A, B, C (referred to in some literature as Bp, Bf, and Bc, respectively) and D, as well as avenacoside A. According to literature avenanthramides A, B and C are the three major forms in oats (9), with avenacoside A as another primary component (27), and thus a targetted approach was followed searching for these compounds. Each standard was diluted with 75% acetonitrile, 25% water, in order to match the sample conditions for solvent composition. Quantifier ions used for identification were; avenanthramide A 298 > 254, avenanthramide B 328 > 284, avenanthramide C 314 > 178, avenanthramide D 282 > 238, and avenacoside A 1107.05 > 1061.45, respectively. Data acquisition and quantification was performed in Labsolutions Insight software (Shimadzu).

2.3.3 Colour analysis

Using a colourimeter, Konica Minolta Chroma metre CR-400, CIELAB system (illuminant C, 10° viewing angle, with an 8 mm diameter port), three repeated measurements were obtained for each sample. The samples were held in a glass cell (diameter 60 mm × 15 mm) and the lightness (L*), red/green coordinate (± a*) and yellow/blue coordinate (± b*) were recorded to give a measure of the lightness and colour.

2.3.4 Particle size analysis

A Malvern Mastersizer S was used to obtain measurements of particle size [suitable for readings above 1 μm (1000 nm)]. Three repeats were carried out, one after the other on the instrument, with the water flushed out between each reading to reduce residual particles. A Malvern nanoseries ZS zetasizer was used to obtain measurements of the polydispersity index. Polydispersity index is a measure of the heterogeneity of a sample based on size, and is determined by dynamic light scattering (28). Each sample (1 ml aliquot in a cuvette) was measured in triplicate, with three technical replicates per aliquot. Data were recorded and analysed using the Malvern zetasizer software. Default settings were selected with Angle 173, with run conditions 25°C for 200 s.

2.3.5 Rheological properties

Rheological properties were studied using a controlled stress rheometer (MCR 302, Anton Paar Ltd. St Albans, UK) using parallel plate geometry (50 mm diameter). OMA samples were frozen and thawed prior to rheological analyses. The gap size was 1 mm and a resting time of 300 s prior to measurement was established for sample relaxation and temperature equilibration. Apparent viscosity was measured as a function of shear rate over the 1 to 1000 s^{-1} range, at 25°C. Measurements were carried out in triplicate for each of the samples, with an average viscosity calculated for each at shear rate 50 s^{-1}.

2.4 Statistical analysis

The quantitative data for each compound identified in the GC-MS and LC-MS analyses, or physicochemical measurements (colour, particle size, PDI, viscosity) were analysed by one-way analysis of variance (ANOVA) using XLSTAT Sensory (Version 2022.5. 1. 1388). For those compounds or physicochemical parameters exhibiting significant difference in the one-way ANOVA, Tukey's honest significant difference (HSD) test was applied for multiple pairwise comparisons. SENPAQ (Qi Statistics, Kent, UK) was used to carry out ANOVA and principal component analysis (PCA) using the covariance matrix, of the sensory panel data. For the sensory data two-way ANOVA was used where the samples were fitted as fixed effects and the assessor as random effects, and both of these treatments were tested against the sample by assessor interaction. Tukey's HSD *post-hoc* test was applied for pairwise comparisons. In all multiple pairwise comparisons, significance was assumed at $p \leq 0.05$. Multiple factor analysis was applied to correlate the means for the sensory data (taken over the assessors) with the means of volatile data.

3 Results

3.1 Sensory analysis

The trained sensory panel agreed to use 35 terms for the quantitative assessment of the samples and the mean panel scores for these attributes are shown in **Table 3**. Overall, 16 out of 34 attributes were significantly different between the six samples. The panellists' individual results were analysed for repeatability and reliability. No obvious anomalies were observed as the panel scored to a consistent standard with one another.

Significant differences were found in all appearance attributes, with sample C displaying the most off-white colour, yet the least froth/foam, bubble size and glass cling. Samples E and F were found to have significantly less off-white colour than all other samples, whilst sample A displayed the most glass-cling. For aroma, significance was found within the overall aroma intensity, wet oats,

TABLE 3 Mean panel scores for sensory attributes of the six OMA samples.

Attributes	Mean score (0–100)[a]						Significance of sample (*p*-value)[b]
	A	B	C	D	E	F	
Aroma							
Overall intensity	32.8^{ab}	26.9^{b}	41.4^{a}	33.3^{ab}	33.5^{ab}	35.8^{ab}	0.002
Sweet	18.0	16.3	22.6	20.9	19.6	21.0	0.172
Wet oat	25.4^{ab}	18.8^{b}	33.6^{a}	27.3^{ab}	27.1^{ab}	31.1^{a}	0.002
Malt	12.7^{a}	2.7^{b}	10.0^{ab}	8.3^{ab}	7.9^{ab}	6.6^{ab}	0.031
Nutty	3.7	1.8	5.9	5.9	4.3	7.8	0.196
Stale	7.0	8.0	8.4	4.4	8.9	6.2	0.670
Single cream	0.4	1.7	0.4	3.0	0.5	2.8	0.183
Brown bread	12.9^{ab}	1.6^{c}	16.8^{a}	10.8^{abc}	15.5^{ab}	6.4^{bc}	0.0001
Appearance							
Off white colour	56.4^{ab}	52.3^{b}	67.3^{a}	50.5^{b}	39.3^{c}	31.0^{c}	$<$0.0001
Glass cling	41.8^{a}	29.9^{b}	24.8^{b}	28.9^{b}	26.0^{b}	35.6^{ab}	$<$0.001
Froth/foam	47.2^{a}	43.6^{a}	26.3^{b}	37.7^{ab}	39.9^{ab}	46.9^{a}	$<$0.001
Bubble size	25.9^{a}	26.3^{a}	14.5^{b}	24.5^{a}	26.6^{a}	28.2^{a}	$<$0.0001
Taste							
Sweet	27.1^{ab}	25.4^{ab}	21.9^{b}	30.4^{a}	28.7^{ab}	25.1^{ab}	0.034
Bitter	12.2	12.3	15.0	9.2	9.7	14.5	0.087
Acid/tang	3.6	7.5	9.8	4.6	5.5	7.3	0.162
Metallic	8.0	9.6	9.4	7.1	7.6	8.8	0.801
Flavour							
Malty	9.7	4.9	6.8	10.5	6.6	4.8	0.260
Wet oats	29.3	27.9	32.6	29.0	29.8	33.1	0.434
Nutty	6.0	6.9	6.2	9.0	9.2	12.2	0.105
Stale	6.7	5.3	7.2	3.8	5.7	4.4	0.653
Single cream	7.3^{ab}	9.5^{a}	0.0^{b}	9.2^{ab}	10.4^{a}	9.2^{ab}	0.024
Brown bread	11.5^{ab}	4.9^{b}	14.8^{a}	10.1^{ab}	11.5^{ab}	6.2^{ab}	0.008
Mouthfeel							
Mouthcoating	32.7	32.0	23.3	26.7	27.3	29.7	0.101
Body	31.5^{a}	26.4^{a}	18.2^{b}	28.8^{a}	26.5^{a}	30.3^{a}	$<$0.001
Powdery	13.8^{ab}	22.8^{a}	22.4^{a}	7.0^{b}	7.1^{b}	6.7^{b}	0.0001
Astringency	14.3	18.8	21.4	13.8	17.6	16.9	0.135
Aftertaste							
Bitter	10.6	9.2	14.0	9.0	9.2	12.6	0.288
Metallic	8.4	10.5	11.5	6.0	7.5	8.8	0.068
Sweet	16.5^{ab}	20.2^{a}	13.3^{b}	17.5^{ab}	19.6^{ab}	16.5^{ab}	0.040
Wet oats	19.4	19.6	23.4	19.8	21.2	24.1	0.387
Single cream	3.1	8.3	0.4	8.0	7.9	5.3	0.023
After effects							
Mouthcoating	18.4	18.6	13.0	17.9	16.6	14.9	0.225
Powdery	11.1	12.9	13.6	4.8	5.6	4.8	0.006
Astringent	19.8	18.3	18.8	14.4	16.7	16.5	0.467
Salivating	20.6	23.5	23.5	20.7	22.2	24.4	0.700

[a]Means not labelled with the same letters are significantly different ($p < 0.05$); means are from two replicate samples. [b]Probability of a significant difference between samples.

malt and brown bread aromas. Overall intensity was highest in sample C, as well as wet oats and brown bread, yet the malty aroma was highest in sample A. In terms of significant differences in taste, sample D was found to be the sweetest, with sample C the least sweet. For flavour, sample C was the highest in the brown bread note, yet was the only sample to score no single cream flavour at all. Significant differences were found in the mouthfeel of the samples, with A scoring the highest in body, whilst sample C was the lowest. Samples B and C also had significantly more powdery mouthfeel than all other samples. For aftertaste, B was found to be the most sweet, with sample C again being the least. There were no significant differences for any other after effects. Although there were no significant differences between samples for astringency, within mouthfeel or as an after-effect, astringency was perceived in all samples. The relationship between this astringency and non-volatile compounds was further evaluated.

3.2 Instrumental analysis

3.2.1 Volatile compounds

3.2.1.1 GC-MS–Optimisation of the extraction conditions

In order to determine the optimal conditions for volatile extraction, sample A was used with varying conditions, based on previous studies of other plant-based alternatives (29, 30), as well as bovine milk (31). The following parameters were evaluated: incubation and extraction temperature (40°C and 50°C), incubation time (10, 20 and 30 min), extraction time (10, 20, and 30 min), and salt (sodium chloride) addition varied from 0, 0.5, 0.75, and 1 g. Optimal conditions were selected considering the overall amount of the extracted volatiles. Increasing salt from 0 to 0.5 g resulted in an improved efficacy of the extraction, however, increasing above 0.5 g showed no additional effect, therefore 0.5 g was selected. Additionally, increasing incubation time above 10 min showed no obvious differences, whereas increasing the extraction time from 10 to 30 min resulted in more abundant peaks. Finally, increasing the temperature above 40°C did not improve efficacy of the procedure, therefore 40°C was selected as the incubation and extraction temperature. In conclusion, the optimal parameters were set at 40°C, 10 min incubation time, 30 min extraction time, and addition of 0.5 g of NaCl.

3.2.1.2 SPME GC-MS

More than 35 compounds were identified in the headspace of the six samples (**Table 4**) including four esters, eleven aldehydes, five ketones, four terpenes, one alkane, three alkenes, three alcohols, and four furans.

Of the esters, sample C was significantly lower in methyl propanoate, methyl butanoate, and methyl 2-methylbutanoate, however, it exhibited the highest abundance in methyl acetate. Samples A and E were generally higher in esters, both being the highest in methyl butanoate and methyl propanoate, whilst A, E and B were significantly higher than C in butanoic acid.

Hexanal was the most abundant aldehyde in the samples, and was significantly higher in sample F, followed by sample C. Sample D exhibited significantly more 2-heptenal and furfural than all others, whilst sample C was found to have high abundance in octanal, 3-methylbutanal and 2-methylbutanal, and was the only sample to contain non-anal. Sample E was the second highest in 3-methylbutanal, 2-methylbutanal and octanal, whilst being the highest in 2-methylpropanal. Sample B was generally found to have low levels of aldehydes such as 2-methylpropanal and heptanal, with no 2-hexanal, furfural, 2-heptenal, octanal or non-anal being detected. B was also significantly lower than all others aside from F in 3-methylbutanal and 2-methylbutanal. Despite being lower in 3-methylbutanal and 2-methylbutanal, F exhibited the highest abundance in heptanal and 2-hexenal, a compound only present in C and F.

Of the alcohols detected, sample F was significantly higher than all others in hexanol and pentanol. Octen-3-ol was present in all samples, with C exhibiting significantly higher abundance than A and E.

In terms of ketones, sample E was abundant in 2-butanone, butanedione, and 3 methyl 2-butanone. 6-methyl-5-hepten-2-one was only detected in sample C, whilst 3-methyl-2-pentanone was detected in only B and C.

Of the furans, 2-pentylfuran was significantly higher in sample E, followed by, A, and then C. Sample B exhibited the lowest abundance in all furans aside from 2-ethylfuran, which it was found to be the second lowest, following sample D.

Most terpenes, including alpha-pinene, beta-pinene and camphene were highest in sample B, whereas limonene was the highest in sample C.

Multiple factor analysis was used to determine correlations between the sensory results and volatile compounds for each sample (**Figure 1**), from which multiple significant correlations were found. Brown bread aroma was found to be significantly positively correlated with 2-methylpropanal, 3-methylbutanal and 2-methylbutanal—all branched chain aldehydes described as having a malty and chocolate aroma (32), as well as with methyl acetate. Brown bread flavour was also significantly positively correlated with methyl acetate, 2-methylbutanal and 3-methylbutanal. 3-methylbutanal is an amino acid-derived key flavour compound in bread, with a fairly low taste threshold (32), which may have resulted in the brown bread aroma and flavour correlation.

A nutty aroma was found to be positively correlated with heptanal, a compound typically described as having a fatty aroma when in isolation (33). Sweet and wet oats aroma were also both found to be significantly positively correlated with heptanal, yet negatively correlated with methyl 2-methylbutanoate.

Wet oats flavour was shown to be positively correlated with hexanal, which often imparts a green aroma (33), as well as with pentanol, 2-hexenal and heptanal, yet was again negatively correlated with methyl 2-methylbutanoate. Single cream flavour was significantly positively correlated with methyl propanoate and 3-methyl-2-butanone, whilst being negatively correlated with benzaldehyde, 6-methyl-5-hepten-2-one, limonene and non-anal.

Sensory attributes malty, stale and single cream aroma, and malty, nutty and stale flavour, were not found to be significantly positively or negatively correlated with any compounds identified in the samples.

3.2.1.3 SPME GC-O

Gas chromatography-olfactometry analysis of the samples yielded a total of 24 distinct odorants in the chromatogram that were of note due to multiple panellists perceiving them, which are

TABLE 4 Volatile compounds identified in the headspace of six samples analysed by SPME GC-MS.

Compounds	LRI[a]	Aroma descriptor[b]	Estimated quantities[c]						Significance (p-value)[d]
			A	B	C	D	E	F	
Esters									
Methyl acetate	515	Sweet	1.57[bc]	1.17[c]	3.73[a]	2.17[abc]	3.56[ab]	1.08[c]	0.001
Methyl propanoate	629	Fruity, rum	8.49[a]	6.28[ab]	2.62[b]	6.36[ab]	8.55[a]	7.06[a]	0.003
Methyl butanoate	720	Fruity, creamy	11.37[a]	7.74[ab]	4.76[b]	9.52[ab]	12.82[a]	9.46[ab]	0.013
Methyl 2-methylbutanoate	775	Fruity	5.46[a]	5.56[a]	2.12[b]	4.57[ab]	5.21[ab]	3.60[ab]	0.020
Aldehydes									
2-Methylpropanal	552	Wet cereal, straw	1.21[bc]	0.70[c]	2.48[ab]	1.24[bc]	2.87a[a]	1.37[abc]	0.002
3-Methylbutanal	649	Fruity	6.29[b]	2.35[b]	15.10[a]	7.08[b]	14.40[a]	2.34[b]	<0.0001
2-Methylbutanal	659	Cocoa	5.11[bcd]	2.39[cd]	10.06[ab]	6.10[bc]	7.77[ab]	1.93[d]	<0.0001
Hexanal	802	Green	94.29[c]	31.76[d]	207.09[b]	54.71[cd]	40.86[cd]	316.31[a]	<0.0001
2-Hexenal	853	Green	nd[c]	nd[c]	1.13[b]	nd[c]	nd[c]	1.89[a]	<0.0001
Furfural	836	Bready	nd[a]	nd[a]	2.65[a]	11.96[a]	nd[a]	nd[a]	0.163
Heptanal	903	Green	3.05[cd]	1.59[d]	6.39[a]	5.75[ab]	4.17[bc]	6.65[a]	<0.0001
(2E)-Heptenal	951	Green	nd[b]	nd[b]	2.37[b]	23.52[a]	5.92b	4.92[b]	<0.0001
Benzaldehyde	959	Almond	1.38[b]	1.26[b]	2.12[a]	0.92[bc]	0.47[c]	1.34[b]	0.000
Octanal	1007	Fruit-like	nd[b]	nd[b]	2.97[a]	nd[b]	2.61[a]	nd[b]	<0.0001
Non-anal	1087	Rose-orange	nd[b]	nd[b]	5.10[a]	nd[b]	nd[b]	nd[b]	0.00
Ketones									
Butanedione	593	Buttery	2.33[c]	1.84[c]	3.58[abc]	5.35[ab]	6.04[a]	2.51[bc]	0.001
2-Butanone	598	Sharp sweet	34.38[ab]	20.47[bc]	12.69[c]	21.60[bc]	42.90[a]	25.24[abc]	0.002
2-Methyl-3-pentanone	749	Mint	nd[c]	6.87[a]	3.21[c]	nd[c]	nd[c]	nd[c]	<0.0001
3 Methyl 2-butanone	661	Camphor	11.10[a]	10.08[a]	3.76[b]	8.73[ab]	11.72[a]	9.10[ab]	0.007
6-Methyl-5-hepten 2-one	787	Citrus, fruity	nd[b]	nd[b]	5.16[a]	nd[b]	nd[b]	nd[b]	<0.0001
Furans									
2-Methylfuran	603	Chocolate	0.67[bc]	0.16[c]	1.26[b]	0.94[bc]	2.37[a]	1.00[bc]	<0.0001
3-Methylfuran	611		0.40[a]	nd[b]	0.32[a]	nd[b]	0.36[a]	0.27[ab]	0.000
2-Ethylfuran	700	Malty, beany	4.53[b]	0.57[d]	2.66[cd]	0.45[d]	1.74[cd]	6.18[a]	<0.0001
2-Pentyl furan	992	Fruity, green	15.50[b]	2.46[c]	12.62[b]	4.55[c]	3.88[c]	33.23[a]	<0.0001
Alkanes									
Octane	800	Gasoline	12.66[c]	132.70[a]	6.32[c]	49.52[b]	120.59[a]	32.43[bc]	<0.0001
1-Octene	794	Gasoline	nd[c]	nd[c]	0.76[c]	14.10[b]	18.65[a]	nd[c]	<0.0001
(E)-2-Octene	804		nd[c]	1.25[c]	0.91[c]	61.49[a]	33.34[b]	nd[c]	<0.0001
(Z)-2-Octene	811		nd[b]	1.17[b]	1.08[b]	31.06[a]	30.96[a]	nd[b]	<0.0001
Terpenes									
α-Pinene	739	Pine	1.88[b]	186.64[a]	1.78[b]	0.34[b]	nd[b]	9.78[b]	0.000
β-Pinene	978	Woody green, pine	nd[b]	35.71[a]	nd[b]	nd[b]	nd[b]	0.51[b]	<0.0001
Limonene	1034	Citrus	0.60[b]	5.63[b]	40.08[a]	0.71[b]	0.59[b]	nd[b]	0.037
Camphene	951	Woody	nd[b]	16.411[a]	nd[b]	nd[b]	nd[b]	nd[b]	<0.0001
Alcohols									
Pentanol	763	fermented	9.77[bc]	2.62[cd]	12.15[d]	4.76[cd]	2.38[d]	27.94[a]	<0.0001
Hexanol	867	Herbal	4.08[b]	nd[b]	0.98[b]	nd[b]	nd[b]	55.01[a]	<0.0001
Octen-3-ol	969	Mushroom	0.88[a]	2.72[abc]	4.30[c]	3.46[bc]	2.29[ab]	4.09[bc]	<0.0001

[a]Linear retention index on a HS-5MS column. [b]Aromas obtained from TheGoodScents company, and PubChem. [c]Estimated quantities (ng) collected from the headspace of 3 mL of OMA sample calculated by comparison with 20 μl of 10 ppm 1,4-dichlorobenzene used as internal standard; means (from three replicate samples) not labelled with the same letter in a row were significantly different ($p < 0.05$); as determined by Tukey's Honestly significant difference (at $p = 0.05$); nd, not detected. [d]Significance of sample effect (p-value).

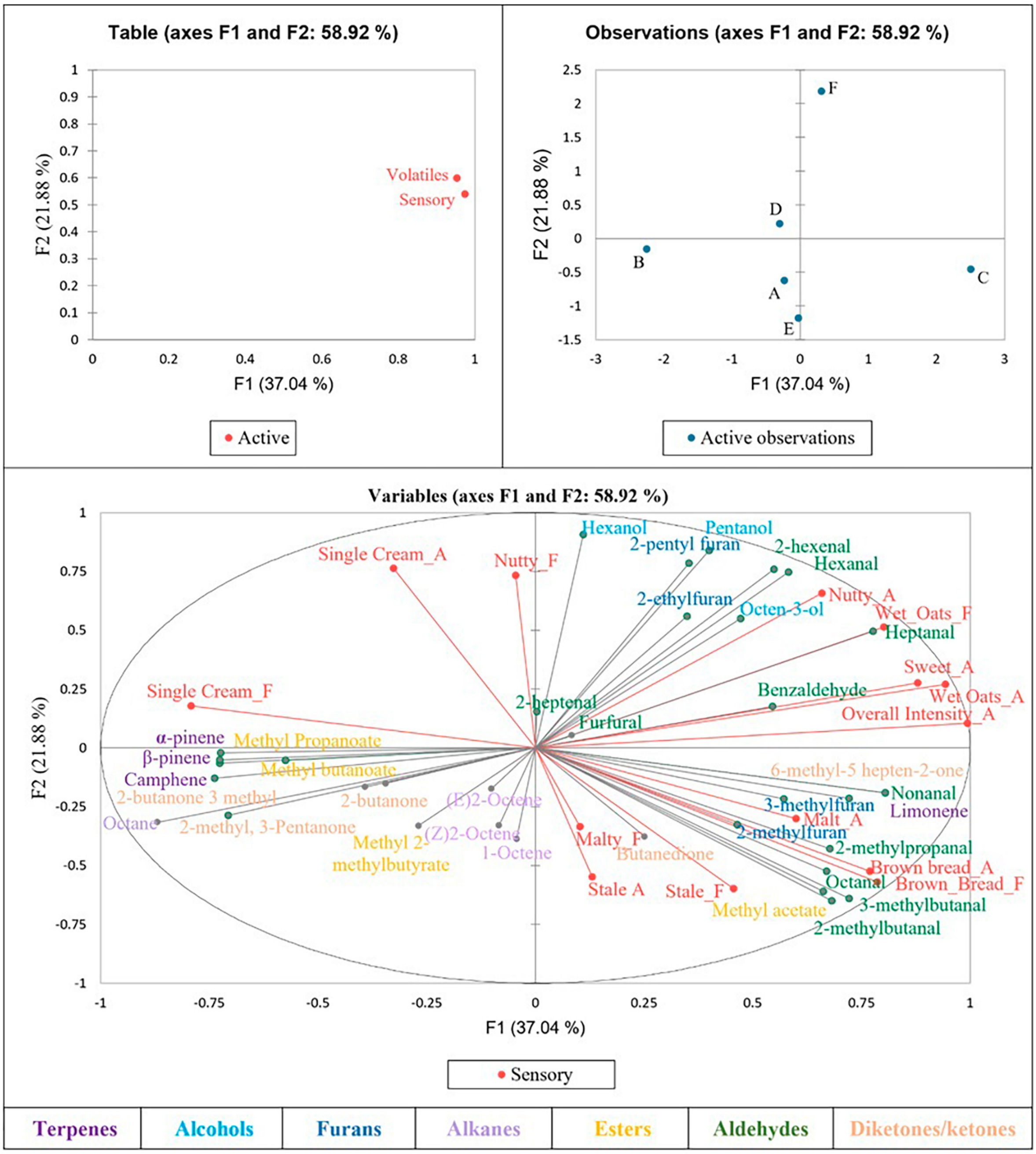

FIGURE 1
Multiple factor analysis correlating sensory data with volatile results.

presented in Table 5. General aroma intensity of all samples was fairly low with only a few strong odours.

Six aromas detected by GC-O were identified in the GC-MS analysis. From Table 5, it can be seen that multiple compounds present in the GC-MS results can be directly associated with detected aromas, due to similar descriptors and LRIs. These included 2-methylbutanal, methyl 2-methylbutanoate, hexanal, and octen-3-ol. Aromas such as buttery and caramel/buttery with LRIs of 552 and 593 (both below 600) in the GC-O were identified as 2-methylpropanal and butanedione based on the GC-MS results.

Other aromas are likely to have resulted from volatile compounds that were not identified by the GC-MS, however, their descriptors and LRIs closely match specific odour compounds present in an internal database used in our lab with authentic compounds ran and analysed at similar conditions. These included 2-methyl-3-furanthiol, methional, 2-furanmethanethiol, 2-acetylpyrroline, 2-isopropyl-3-methoxypyrazine, guaiacol, and 2,6-dimethylphenol. Eleven other aromas were found within the GC-O results, however, an associated volatile compound for these aromas was not found, suggesting they were highly odour active compounds and below the limit of detection of the GC-MS.

TABLE 5 Mean GC-O scores from 3 assessors.

Odour description[a]	LRI[b]	Compound	Confidence[c]	A	B	C	D	E	F
Milk/butter/cheese	<600	Unknown				2			
Butter	<600	2-methylpropanal	A			3			4
Caramel/buttery	<600	Butanedione	A	3.5	5.3	5	3.5	3.8	3.3
Cocoa	651	2-methylbutanal	A			4			
Sulphur/toast	667	Unknown			4.3		3	2	
Boiled milk	675	Unknown		2		2			3
Oat milk/buttery	741	Unknown				2		2	3
Fruity/sweet	767	Methyl 2-methylbutanoate	A			3.5		2	
Green/citrus	801	Hexanal	A	3.4	4.4	4	2.7	3	3.7
Soily/herb	849	Unknown					2.5	5	
Marmite/yeast	873	2-methyl-3-furanthiol	B		4.5		3.5	3.3	4
Soily/wood	885	Unknown		2.7					
Potatoes	874	Unknown		3.3	5		4.7		
Soup/bread/potato	911	Methional	B	4.3	4.8	3.8	3.7	3.5	3.6
Coffee	913	2-furanmethanethiol	B		6				5
Starch/wheat/wet bread	918	Unknown			3.5				5
Cereal/buttery biscuits	930	2-acetylpyrroline	B		3	4		3	3
Mushroom	982	Octen-3-ol	A	4.2	3.8	4.6	5.2	4.2	5.2
Green chemical	992	Unknown			4	3	3.5	3.3	
Soil/mushroom/mould/coffee/wood	1097	2-isopropyl-3-methoxypyrazine	B	2	4.5	5.3	3	3.3	
Toasted bread/smokey meat	1099	Guaiacol	B	4	4.3	4.3	3		3
Ink/chemical	1104	2,6-dimethylphenol	B						4
Sweet milk/caramel	1116	Unknown			3.7				
Cocoa/makeup powder/dusty/soil	1161	Unknown		3.5	4	4.3	2.5		4

[a]Odour description given by assessors (some terms were grouped together due to similarity of the meaning). [b]Linear retention index calculated from a linear equation between each pair of straight chain n-alkanes C_6–C_{25}. [c]Confidence in accuracy of associated compounds; A = LRI in agreement with those of authentic compound–compound present in the GC-MS results; B = LRI in agreement with those of authentic compounds, however, the compound was not present in the GC-MS results. The associations with the compounds found, were based on aroma descriptions from Pubchem, and thegoodscentscompany, and the LRIs and quantities found from an internal database with compounds analysed under similar conditions in our lab.

3.2.2 Avenanthramides and avenacosides (LC-MS/MS)

Figure 2 shows that avenanthramides A, B and C were present in all samples. Avenanthramide D was measured above the limit of detection (LOD), however, was below the limit of quantification (LOQ) in all samples, and therefore has not been included in the results.

Avenanthramide B was detected in the higher concentrations in all samples, in comparison to avenanthramides A and C, which is to be expected due to it being the most abundant of these compounds in oats. Figure 2 shows that samples C and D were significantly higher in avenanthramide B, than all other samples, whilst sample F was significantly lowest in both. However, avenanthramides A and C, were found to be significantly highest in sample B.

Figure 3 demonstrates that avenacosides were present in higher concentrations than avenanthramides in the OMA samples. However, the levels did not follow the same patterns with avenanthramides, with sample F being significantly highest, and B and C significantly lower in avenacoside A than all other samples.

3.2.3 Colour analysis

Figure 4 shows that the lightness for all samples was significantly different. Sample C measured the lowest lightness and F the highest, followed by E. However, figure 4 also shows that D, F, and A all had significantly more green note than C, whilst D had significantly more of a yellow colour.

3.2.4 Particle size analysis

Figure 5 shows that sample C had significantly larger particle size, being the highest in volume weighted mean, surface weighted mean, and median particle size. Sample E and F generally measured lower in particle size, with F measuring the lowest in volume weighted mean, and E the lowest in surface weighted mean, and median particle size.

Figure 6 indicates that sample A measured the highest reading for polydispersity index, significantly higher than all others, aside from C. Samples E and F measured significantly lower polydispersity index than all other samples.

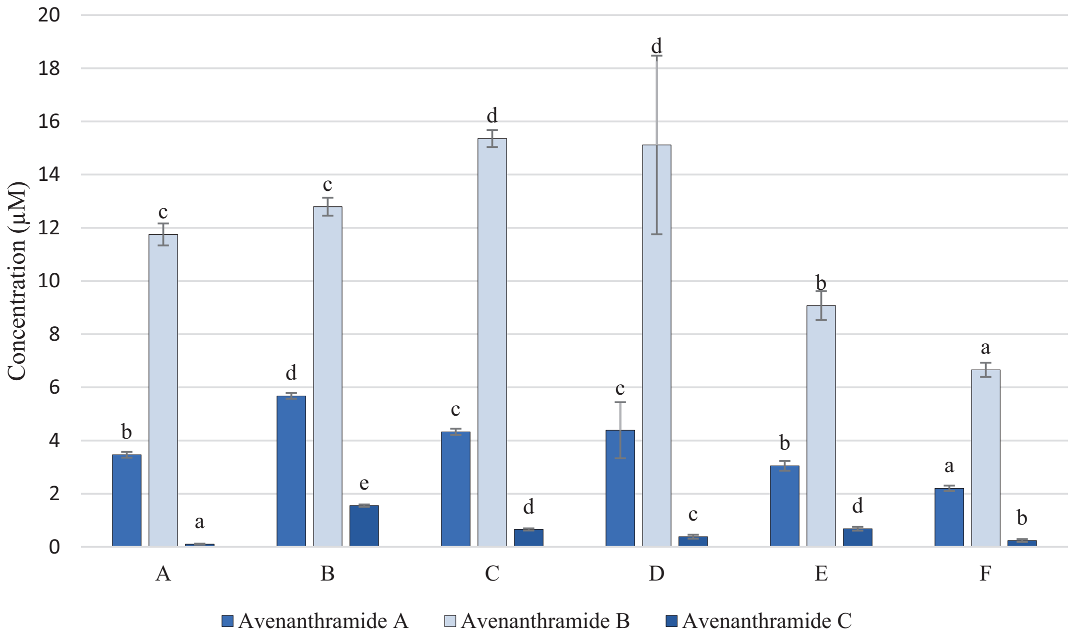

FIGURE 2
Concentration of Avenanthramides (μM in OMA sample). Data represents means of three instrumental replicates of three sample replicates ± standard deviations (p-value < 0.0001). Differing small letter represent sample significance from multiple comparisons as determined by Tukey's honestly significant difference (at p = 0.05).

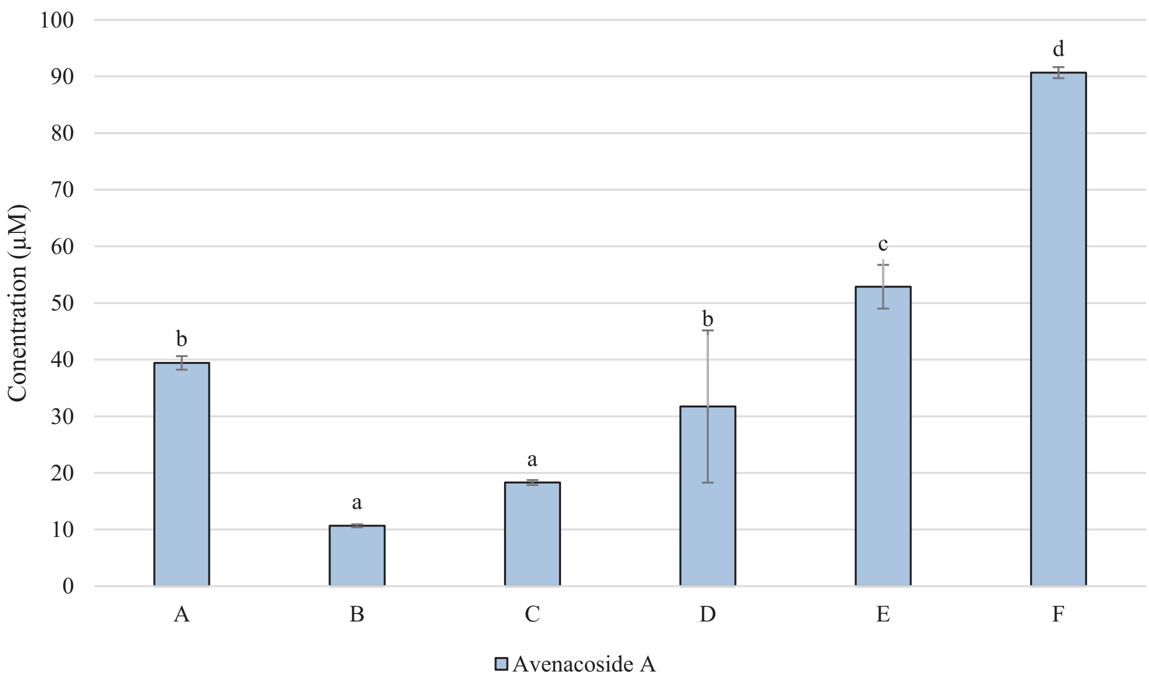

FIGURE 3
Concentration of Avenacoside A (μM in OMA sample). Data represents means of three instrumental replicates of three sample replicates ± standard deviations (p-value < 0.0001). Differing small letter represent sample significance from multiple comparisons as determined by Tukey's Honest significance difference (at p = 0.05).

3.2.5 Rheological properties

Figure 7 shows that all samples decreased in viscosity with increasing shear rate, indicating that these products show non-Newtonian shear thinning behaviour ($N < 1$). Samples B, C and D were higher in viscosity and a larger drop in viscosity with increasing shear rate, in comparison to samples A, E and F, at lower shear rates ($<100^{-1}$). At higher shear rates, however ($>500^{-1}$), shear thickening behaviour can be observed, with a slight increase

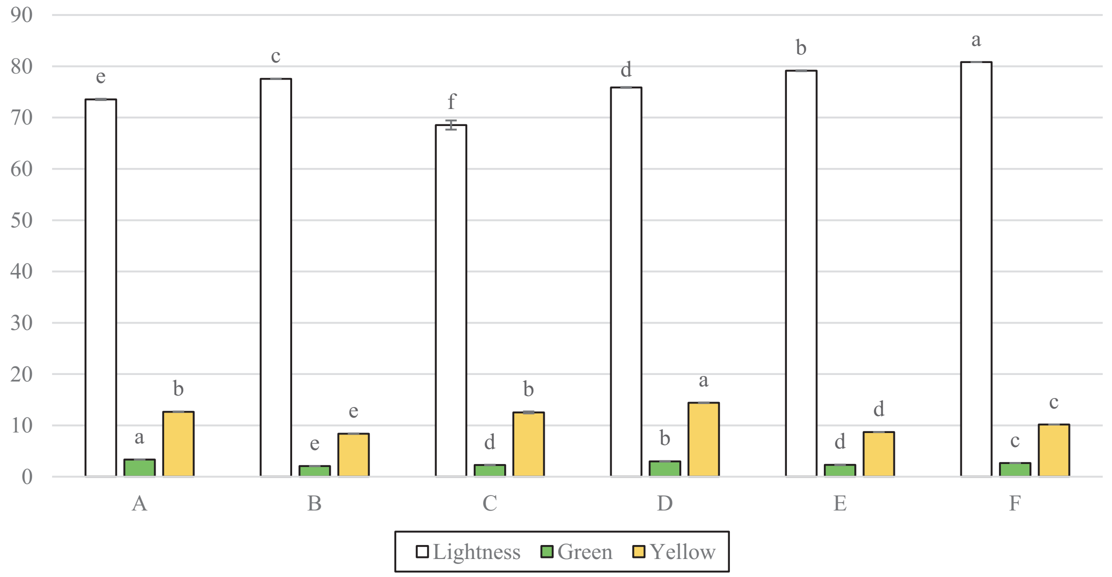

FIGURE 4
Colorimetre readings for lightness (L*) green direction (a*) and yellow direction (b*). Data represents means of three replicates ± standard deviations (p-value < 0.0001). Differing small letter represent sample significance from multiple comparisons as determined by Tukey's HSD (at p = 0.05). Green note was measured in minus values, converted to positives for clarity on graph.

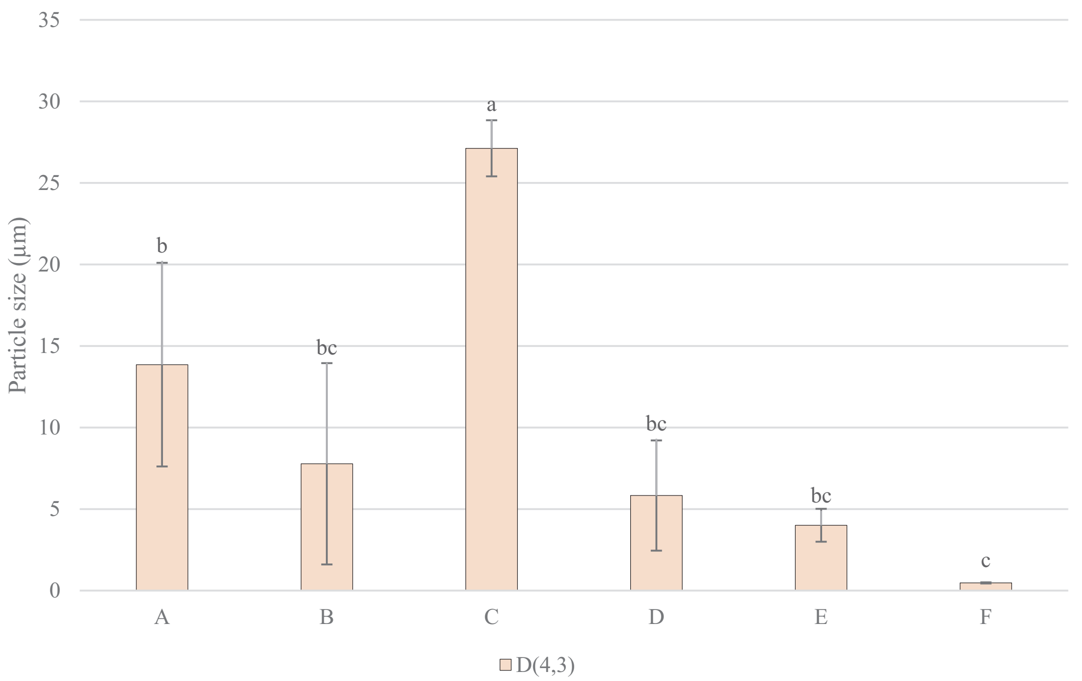

FIGURE 5
Particle Size Measurements: D, 4, 3 (volume weighted mean/mass moment mean diameter) mm. Data represents means of three replicates ± standard deviations (p-value < 0.0001). Differing small letter represent sample significance from multiple comparisons as determined by Tukey's HSD (at p = 0.05).

in viscosity in all samples. However, it may be the case that the viscosity recordings above 500^{-1} are outside of the experimental limit, leading to this increase in viscosity as a result of experimental error (34). Sample C contained the highest carbohydrate content as shown in Table 2 and was also found to have the highest viscosity at lower shear rates.

A comparison of samples at shear rate 50 s^{-1} is often used as this is thought to represent the shear rate of the oral cavity, however, it is important to note that there more recent studies have shown a large range of sheer rates from 1 to 1000 s^{-1} (35). The mean values of viscosity of the samples at this shear rate are given in Table 6. Samples C and D were found to demonstrate a

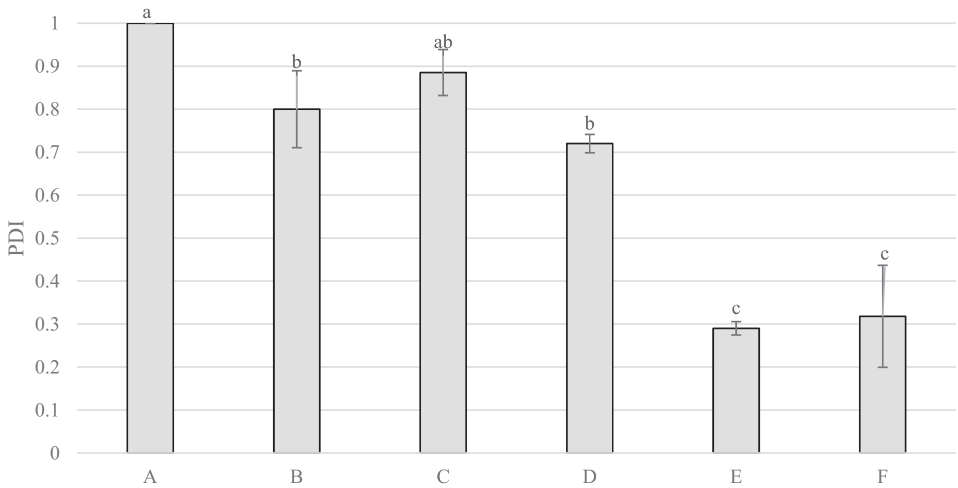

FIGURE 6
Polydispersity Index (PDI) of non-filtered samples. Data represents means of three replicates ± standard deviations (p-value < 0.0001). Differing small letter represent sample significance from multiple comparisons as determined by Tukey's HSD (at p = 0.05).

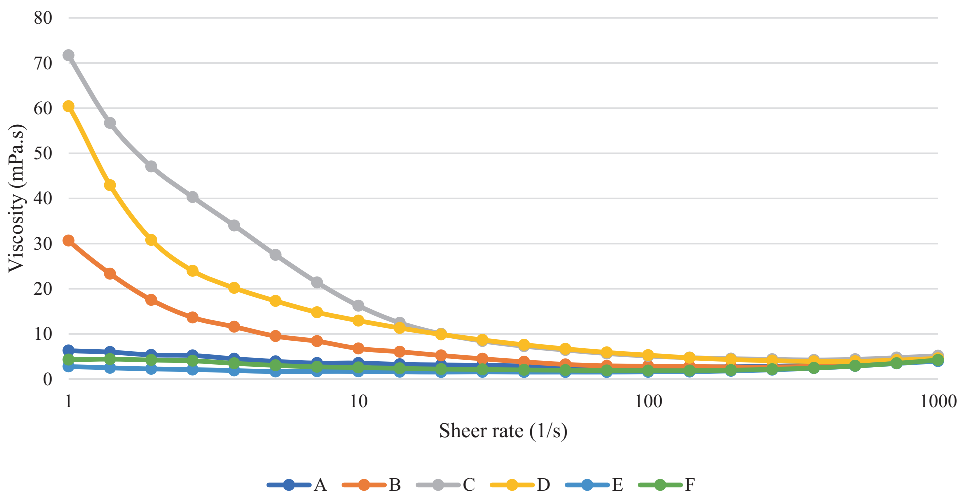

FIGURE 7
Sample viscosity as a function of shear rate.

TABLE 6 Viscosity values of samples at shear rate 51.8 (1/s).

Sample	A	B	C	D	E	F
Viscosity (mPa.s)	2.83^{bc}	3.24^{c}	6.42^{d}	6.68^{d}	1.54^{a}	1.95^{ab}

Data represents means of three replicates. Differing small letter represent sample significance from multiple comparisons as determined by Tukey's HSD (at p < 0.05).

significantly higher viscosity than all others at this shear rate, whilst sample E was significantly lower, at 1.54 mPa.s.

3.2.6 Extent of separation

Figure 8 demonstrates the visible separation after 24 h in samples A, C and F. With sample A having the highest PDI, and C the highest volume weighted mean, this suggests that increased PDI and particle size may relate to increased separation. However, it does appear from figure 8 that separation is also occurring in sample F, despite having a much lower particle size and PDI. It is not entirely clear as to why this may be the case, however, it is likely that this is due to other factors such as stabilisers used; Table 1 shows that F did not contain any stabilisers, whilst some of the less separated samples contained stabilisers including plant fibres and gellan gum.

4 Discussion

4.1 Avenanthramides and avenacosides in relation to ingredients and sensory attributes

Oat concentration did not appear to be directly influencing the perceived astringency of samples, as samples highest in oat content

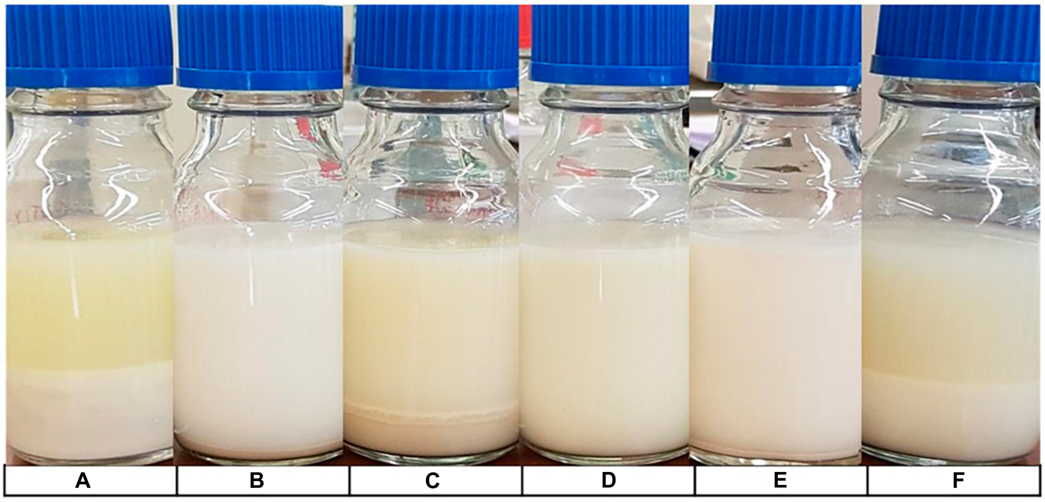

FIGURE 8
Extent of separation. Samples stored in glass vials for 24 h at 5°C for visual comparison of separation. Order from left to right: **(A–F)**.

did not score higher in astringency. Nor was a trend found between protein content and astringency, despite an association within literature between protein and astringency (36). Avenanthramides and avenacosides are known to contribute to both astringency and bitter taste (20); sensations that were present at low levels in all samples. However, the samples did not differ in these attributes; samples with higher concentrations in these compounds were not detected as more astringent or bitter. Therefore, we suggest that the differences in avenanthramides and avenacosides between samples were below their just-noticeable-difference thresholds.

It is possible that the levels of astringency may be affected by other factors, including acids, dehydrating agents, and salts (37). In addition, the lipid content of the samples may have masked the perception of astringency (38). Sample C had the lowest fat content, and sample A had the highest (**Table 2**). However, although the mean astringency value was highest in C and amongst the lowest in A, which fits the lipid hypothesis, these differences in mean astringency values were not significant. Overall, whether the level of astringency and bitterness found in the samples would be detected by untrained consumers, and whether it is a factor in consumer acceptance, requires further investigation.

It is apparent from the LC-MS results that the levels of avenanthramides and avenacoside did not reflect the oat content (**Table 1**); with samples C and D containing the lowest quantities of oats, yet the highest overall concentration of avenanthramides. Sample B contained the highest quantity of oats, yet the lowest concentration of avenacoside A. With oats being the only possible source of these compounds, this may suggest that loss is occurring throughout stages of production. Phenolic compounds in oats have been found to decrease by 85% after the first 6 months of storage and remain at that level for the rest of the 12 months storage (39). This may suggest that the differences in phenolic compounds found within the 6 samples, may be related to storage time. Differences in the oat genotype and growing conditions may also affect the concentration of avenanthramides in the oat material (40). The differences in concentrations between avenanthramides and avenacosides, may suggest that certain compounds are more or less susceptible to degradation or loss than others. Steaming of oats has previously been shown to moderately reduce content of avenanthramide A, yet not affect avenanthramides B and C (9). Total avenanthramide concentration in oats has been found to range from 1.2 to 79.7 mg/kg, depending on the genotype (41). The total concentration of avenanthramides A, B, and C combined in the samples ranged from 8.6 to 25.9 μM, which is the equivalent of 0.00973–0.0293 mg/kg. This is substantially lower than what has been found in the literature, however, it is important to consider the high moisture content of the samples, in comparison to pure dehulled oat grain.

Within the sensory results sweet taste was found to be significant, with sample D measuring a significantly sweeter taste than sample C. This does not, however, match the nutritional information shown in **Table 2**, which shows D and B to contain the least quantity of sugar, with C the most. It is not clear as to why this may be the case other than these differences in sugars being below the threshold of noticeable differences for taste. The sweet taste perception may also be more complicated than just the reported level of sugar, due to the presence of complex carbohydrates (42).

These findings suggest that the effect of ingredients on the sensory profile is complicated and therefore may be difficult to predict.

4.2 Relationships between volatile compounds and sensory attributes

Steaming of oats has been shown to increase the concentration of certain compounds, including 3-methylbutanal, benzaldehyde, heptanal, hexanal, and 2-pentylfuran, whilst the combined effect of kilning and steaming may boost the amount of Maillard reaction-related volatiles (43). This may suggest that samples with higher concentrations of these compounds may have been affected by processing. Of these, a significantly higher abundance of benzaldehyde, was measured in sample C. Benzaldehyde has been suggested to likely result from interactions of reducing sugars and amino acids (44), and has been shown to significantly increase during storage of processed oats (39). Many other volatile compounds were also significantly higher in sample C, including nonanal, 6-methyl-5-hepten-2-one, limonene, and octen-3-ol. This increased abundance of many volatiles in sample C may have resulted in the significantly higher overall aroma as determined by the sensory panel, as well as the total of 15 distinct aromas detected in the GC-O analysis – the joint highest amount alongside sample B. Processed oats have been found to emit a higher odour than native oats (39), again suggesting this sample may have been affected by processing.

Differences in oat varieties have been shown to significantly affect sensory characteristics, including oat aroma, bitter taste, metallic, oat and creamy flavour, and oats and metallic after flavour (45). This may have contributed to the differences seen in the sensory results. Sample C was found to have the highest stale flavour by the sensory panel, although not significantly, as well as containing significantly higher 3-methylbutanal than all other samples. This may be associated with the reference of flaked almonds used by the panel for the attribute of stale, as 3-methylbutanal is described as one of the most predominant compounds in roasted almonds (46). This could also be related to the presence of benzaldehyde, an aroma associated with almonds (33), in which sample C measured significantly higher than all other samples. Methyl acetate, 3-methylbutanal, octanal, non-anal, 6-methyl-5 hepten-2-one and limonene, are all described as a sweet or citrus aromas, and could potentially have influenced the highest sweet aroma found in the sensory results, and the highest caramel note and fruity/sweet aromas within the GC-O results.

Hexanal, which has been shown to be the predominant aldehyde in oats (47), was also found to be the most abundant aldehyde in these samples. Hexanal is a lipid oxidisation product, which has been shown to increase during storage periods of processed oats (39), and therefore may have been affected by photo-oxidation from the clear plastic packaging in sample C, leading to the increased abundance. Photo-oxidation in oats may occur during processing, and is one of multiple reactions that can trigger the formation of lipid derived volatile compounds that may exhibit off-flavours (43). Differences in hexanal may also result from the possibility of a protein rich kernel to eliminate hexanal, as well as from variability of process conditions (48), having been shown to rapidly rise after heat treatment (47).

Sample B had the lowest mean overall aroma intensity, brown bread and wet oats aroma as determined by the sensory panel. This may have been influenced by the limited volatiles, as this sample was also found to have the lowest mean abundance in 16 of the compounds measured in the GC-MS; significantly lower than sample C in 14 compounds. Sample B exhibited the lowest abundance in all furans aside from 2-ethylfuran, in which it was found to be the second lowest, following sample D. Thermal processing is reported to be a main cause of furan formation, occurring to a large extent during the Maillard reaction (49).

Multiple factor analysis also found multiple correlations between the sensory results and volatile compounds, including sweet, wet oats and nutty aromas with heptanal, and brown bread aroma with methyl acetate, 2-methylpropanal, 3-methylbutanal and 2-methylbutanal. Wet oats flavour was shown to be positively correlated with pentanol, hexanal, 2-hexenal and heptanal. Single cream flavour with methyl propanoate, and 3 methyl 2-butanone, and brown bread flavour with methyl acetate, 3-methylbutanal and 2-methylbutanal. Such correlations do not necessarily indicate that the volatile compounds are responsible for the resulting flavours, they can be incidental correlations where volatiles group together. However, from the literature we can reflect that some volatile compounds may be influencing these sensory characteristics; for example branched chain aldehydes, specifically 3-methylbutanal, being flavour compounds associated with bread (32), whilst positively correlating with brown bread aroma and flavour.

The stale aroma which was detected in low levels in all samples by the sensory panel may be related to the highly scoring mushroom aroma picked up in every sample during the GC-O and identified as octen-3-ol. Despite the low concentrations of octen-3-ol detected, this compound has a very low odour threshold (>1 ppb) and may indicate an off-odour in oats (50). Octen-3-ol is produced by lipid oxidation, and increases greatly with storage time (51), therefore due to oats high lipid content, and active lipolytic enzymes (50), this may have resulted in the octen-3-ol detected within these samples. The sweet aroma detected in all samples may relate to the caramel note detected highly within all samples in the GC-O results and identified as butanedione.

4.3 Lightness, particle size, and rheology properties

The sensory results demonstrated that samples F and E were perceived to have the least off-white colour, with sample C the most. A similar finding was presented in the colourimeter results, as C was again found to have the least lightness, with F measuring the highest lightness, followed by E. The colour measurements did not find C to have more red or green colour than the other samples, which suggests that the off-white colour perceived by the panel, is due to lack of lightness, rather than influence from colour. The particle size measurements showed samples F and E to be the smallest, which may have influenced the increased lightness as a result of light scattering (17), and thus supports the hypothesis that lower particle size may contribute to increased whiteness.

The sensory results demonstrated that C was significantly more powdery than D, E, and F, as well as having the most powdery after effect. This also corresponds with particle size, as sample C was measured to have the largest volume weighted mean, and F the least, suggesting that larger particles may be resulting in a powdery mouthfeel and after-effect.

The rheology measurements found sample C to be the most sheer thinning during the lower sheer rates (below 10 mPa.s), followed by B and then D. This negatively correlates with the fat content listed in the nutritional information, with sample C containing the lowest fat content, followed by B and D. Sample C also exhibited the highest particle size which may have affected the rheology. OMAs in general have been shown to have a higher viscosity than other plant-based milks, potentially due to a higher carbohydrate content (52). This is also seen in sample C with the highest carbohydrate content, and generally higher viscosity at lower sheer rates.

This study may have been affected by slight limitations in analytical conditions. Due to the various methods used, it was not possible to carry out all of the sensory, chemical and physical analyses on the same batch at the same time. Also due to product C ceasing to be manufactured, which was out of the control of the study, all products needed to be frozen and thawed between sets of analyses. In ideal conditions all samples would have been analysed fresh, after opening the same day. However, all of the six products were analysed in the exact same conditions, all being frozen and thawed at the same time, therefore the difference in findings between the samples will still be an accurate representation.

5 Conclusion

The combined results from all six samples help to conclude influences between the physicochemical, sensory, and volatile properties, along with effects from ingredients and packaging. These include the likelihood that smaller particle size may lead to increased lightness and less perceived off-white colour, as well as reduced powdery mouthfeel—which may be beneficial for the sensory profile. Smaller particle size, as well as the potential addition of stabilisers may both contribute to a decreased separation. The results also suggested that certain compounds were detected in higher abundances in the GC-MS analysis in the clear-packaged non-UHT sample—potentially resulting from photo-oxidation. This appeared to have contributed to perceived aromas through GC-O, and through sensory results, suggesting that the avoidance of clear packaging may help to prevent off-notes.

The results also demonstrated that avenanthramides and avenacosides were present in all samples, which may be beneficial for determining the nutritional value of oat-based milk alternatives. These compounds were not only present, but significantly different between samples and not directly related to the differences in oat content. This may suggest that future analyses on the effects of processing, storage and packaging on these compounds, may be very beneficial to ensure preservation. The lack of significant differences between the samples for bitter taste and astringency, despite differences in avenanthramides and avenacosides, may suggest that there is the potential to increase these compounds without having a negative effect on the sensory profile. These results may be useful in combination for considerations of future OMA development, to improve the sensory profile and nutritional content going forward.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval were not necessary for this study as the study involved tasting standard commercial samples by a trained sensory panel that are employees and have consented to taste and rate food as part of their job.

Author contributions

RM: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing, Conceptualization. LM: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review and editing. SG: Supervision, Writing – review and editing. RE: Conceptualization, Funding acquisition, Supervision, Writing – review and editing. SL: Conceptualization, Funding acquisition, Methodology, Software, Supervision, Validation, Writing – review and editing.

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Conflict of interest

SG was employed by Arla Foods amba.

The remaining 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2024.1345371/full#supplementary-material

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