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REVIEW

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Meat quality, safety, dietetics, environmental impact, and alternatives now and ten years ago: a critical review and perspective

Yelena Oleinikova[1*], Sviatoslav Maksimovich[1], Irina Khadzhibayeva[2,3], Elana Khamedova[1], Aizada Zhaksylyk[1,4] and Aigul Alybayeva[1]

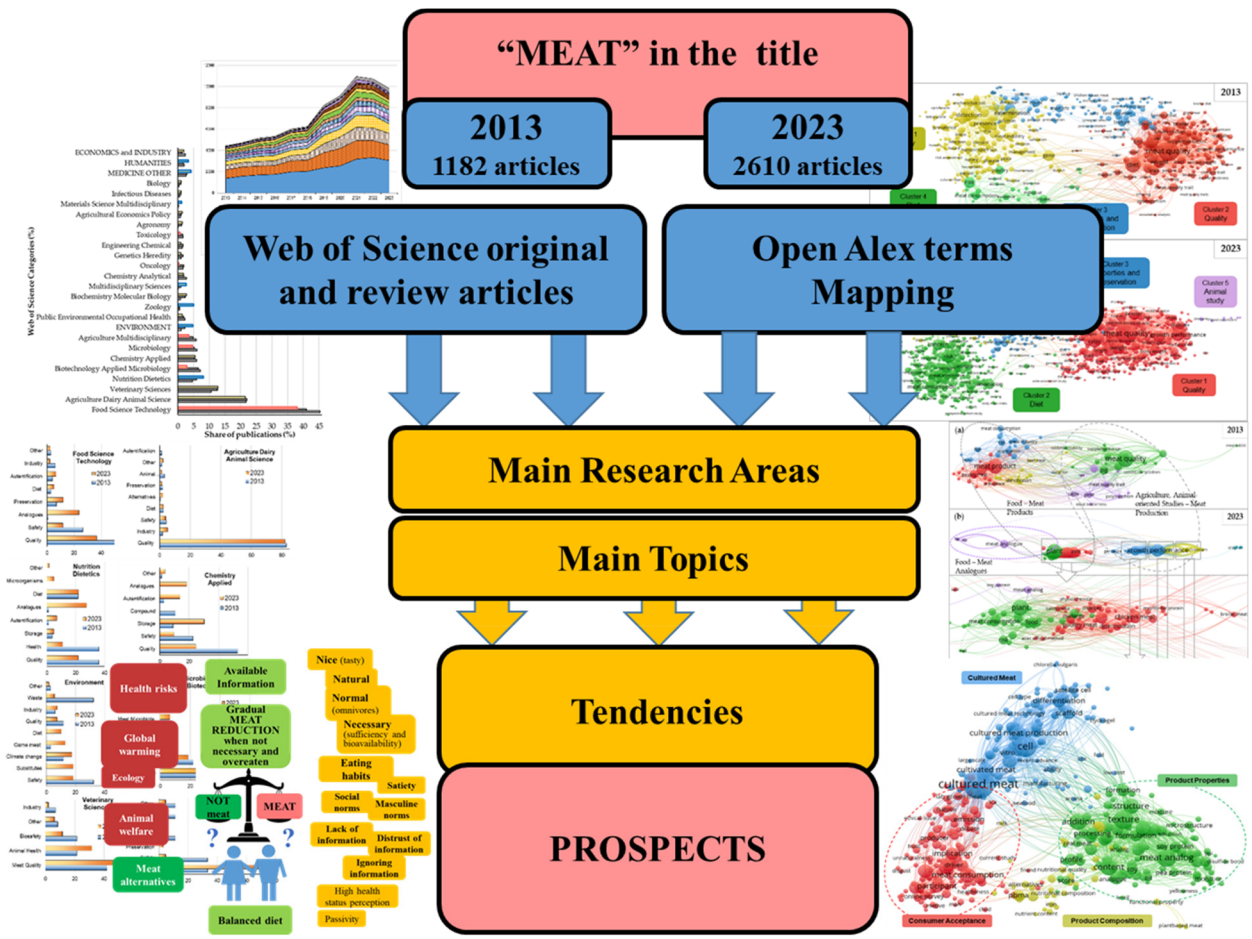
Abstract

Meat consumption is growing steadily. As with any research, meat investigation requires an overall view of the study field to identify current directions and reveal prospective trends. The number of publications on meat research is growing steadily and reaching several thousand publications per year. This creates difficulties in covering all available information in the field and forces researchers to increasingly limit themselves to narrow issues in their direction. We analysed the main trends in meat research published recently and ten years ago. We identified areas of research in the field of meat based on abstracts of articles with the word "meat" in the title published in the Web of Science database in the time intervals 2000–2003, 2010–2013 and 2020–2023. We also mapped terms from articles directly related to meat using VOSviewer and the OpenAlex application programming interface. Among the selected dominant directions of the Web of Science, research areas were systematised based on abstracts of articles and reviews: 1182 publications in 2013 and 2610 publications in 2023. Such an increase in the number of publications indicates a sharp rise in interest in the topic and the existence of questions that need to be resolved. Therefore, an overview of the main directions in meat research in 2013 and 2023 was presented. Research areas with a declining share of articles and actively developing directions were identified, and unresolved pressing questions and trends were presented. The revealed changes demonstrate a shift from microbiology and technology of obtaining meat and meat products towards research methods development, problems of nutrition, and global warming. In conclusion, the prospects for research in these areas have been considered. The need to regulate the negative effects of meat production and consumption justifies the rationality of interdisciplinary approaches integrating environmental, health, and ethical perspectives. The most promising areas for further research are rationale and developing strategies to reduce meat consumption.

Keywords Meat quality, Dietary supplement, Meat safety, Meat consumption, Meat analogue, Cultured meat, Meat reduction

*Correspondence:
Yelena Oleinikova
elena.olejnikova@mail.ru; elllena.olejnikova@gmail.com
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Meat has been a staple food and a source of protein and nutrients for centuries and millennia. Meat consumption is growing every year worldwide (FAO, 2024; Raihan, 2023). It has grown so much that its growth rate is beginning to frighten with the impact on the environment and the impossibility of further increasing the production rates to feed a growing humanity. Research in any field often suffers from a narrow focus and lack of an outside perspective that covers a broader area, allowing one to grasp the general trends in the development of the object of study. Meat research also lacks an overall view of individual narrow areas, as well as an interdisciplinary approach to adjust meat production in accordance with the areas it influences. Therefore, we analysed the main trends in meat research published recently and ten to twenty years ago. The Web of Science database was searched for original and review articles with the word "meat" in the title. Book chapters, conference proceedings, and retracted and withdrawn publications were excluded from the request. The Web of Science areas with the greatest contribution to meat research were selected for analysis. Within the Web of Science directions with the main contribution to meat study, the main research areas were highlighted in the time intervals 2000–2003, 2010–2013, and 2020–2023. Time intervals of several years with a 10-year shift were chosen to fully cover the research in the specified intervals and, at the same time, clearly track changes that have occurred over a longer period, such as a change in the main research directions, clear progress, or a noticeable gap in knowledge in a particular area. In selected priority areas, all experimental and review articles published in 2013 and 2023 were systematised according to topics based on titles and abstracts. The main issues and trends in meat research were identified in each topic. Next, we

analysed meat research in 2013 and 2023 in identified focus areas with dominant and increasing contributions and presented the analysis by topic. The main research trends and advances in the meat field are given, taking into account the full texts of abstract-selected studies in leading and expanding areas. This review aims to identify key research areas, unresolved questions, and emerging trends in meat research over the past two decades.

Web of Science categories covering meat publications

Over the entire period, more than 42,000 original articles and reviews have been published directly related to the meat topic, that is, with the word "meat" in the title. Since 2011, the annual number of publications directly related to meat has exceeded 1,000, and since 2019 has exceeded 2,000. The number of publications in the field of meat has grown steadily over the past 10 years, which is a general trend in scientific publications in recent times. There is also an obvious surge in the total number of publications in 2019 and the immediate subsequent years associated with the COVID-19 quarantine period, as well as a noticeable decrease in published articles after 2021 (Fig. 1). The diagram presented in Fig. 1 shows the Web of Science categories leading in the number of publications in the field of meat. The expansion of research in various categories of Web of Science and the need for more detailed structuring for a clear orientation in the development of the research object is obvious.

Web of Science categories that included a share of publications on meat (with "meat" in a title) of more than one percent were analysed. Periods of several years (2000–2003, 2010–2013, and 2020–2023) were chosen to average the annual fluctuations. Some directions from close areas were combined. For example, Environmental Sciences were grouped with Environmental Studies, Ecology, Environmental Engineering, and Green Sustainable Science Technology. Likewise, MEDICINE included general internal medicine, immunology, parasitology, endocrinology metabolism, medical chemistry, and other directions; HUMANITIES combined behavioural sciences, different directions of psychology, sociology, ethics, cultural and connected studies; and ECONOMICS and INDUSTRY block included various aspects of economics, business, along with engineering industrial, manufacturing, and mechanical. The largest number (77.75–72.35%) of publications on meat in these periods was represented in three directions: Food Science Technology, followed by Agricultural Dairy Animal Science, and Veterinary Sciences. A gradual decline of 7.29% in the number

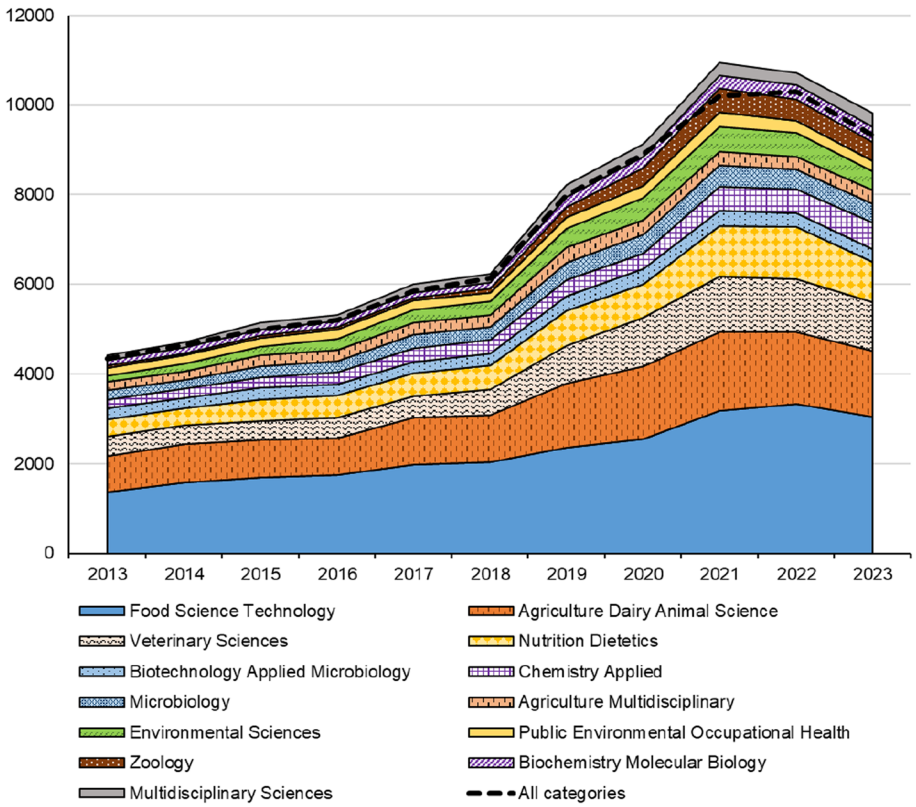


Fig. 1 Total number of publications with the word "meat" in the title in the main categories of Web of Science in 2013–2023

of publications over the past 20 years was revealed in Food Science Technology (Fig. 2). At the same time, there was an increase in articles in Multidisciplinary Sciences, Materials Science Multidisciplinary, as well as some directions connected to medicine and humanities. Also, if in 2000–2003 original articles and reviews with the word "meat" in the title covered 138 Web of Science categories, then in 2020–2023 similar studies already included 195 directions. However, over the past 10 years, such changes have not affected the areas that occupy the second (Agriculture Dairy Animal Science) and third (Veterinary Sciences) places in terms of publication volume in the field of meat. On the contrary, in 2010–2013 the percentage of publications in the field of veterinary medicine even increased slightly. Also, the share of publications in the Chemistry Applied direction has not changed, consistently contributing about 5% to the research area. Therefore, the observed decrease in the contribution of publications in the field of Food Science Technology is not a consequence of the general decrease in publications after the post-COVID increase but is primarily due to the reduction in the number of studies in food technology.

A steady increase in the share of research in the field of Nutrition Dietetics (share from 4.65% in 2000–2003 to 8.09% in 2020–2023) and a significant decline in research in microbiology, primarily in Biotechnology Applied Microbiology (from 7.16% to 2.80%), were noted among the other directions. The share of medical research in toxicology and oncology fields has also decreased. The slight decline (by 2.45%) in publications in the Agriculture Multidisciplinary direction is possibly due to the expansion of the number of other categories in this area and a clearer assignment of published works to certain sections. At the same time, the percentage of research in Zoology has sharply increased (from 0.61% in 2010–2013 to 5.03% in 2020–2023) and the contribution of environmental science research has grown steadily (from 1.04% in 2000–2003 to 4.73% in 2020–2023) (Fig. 2).

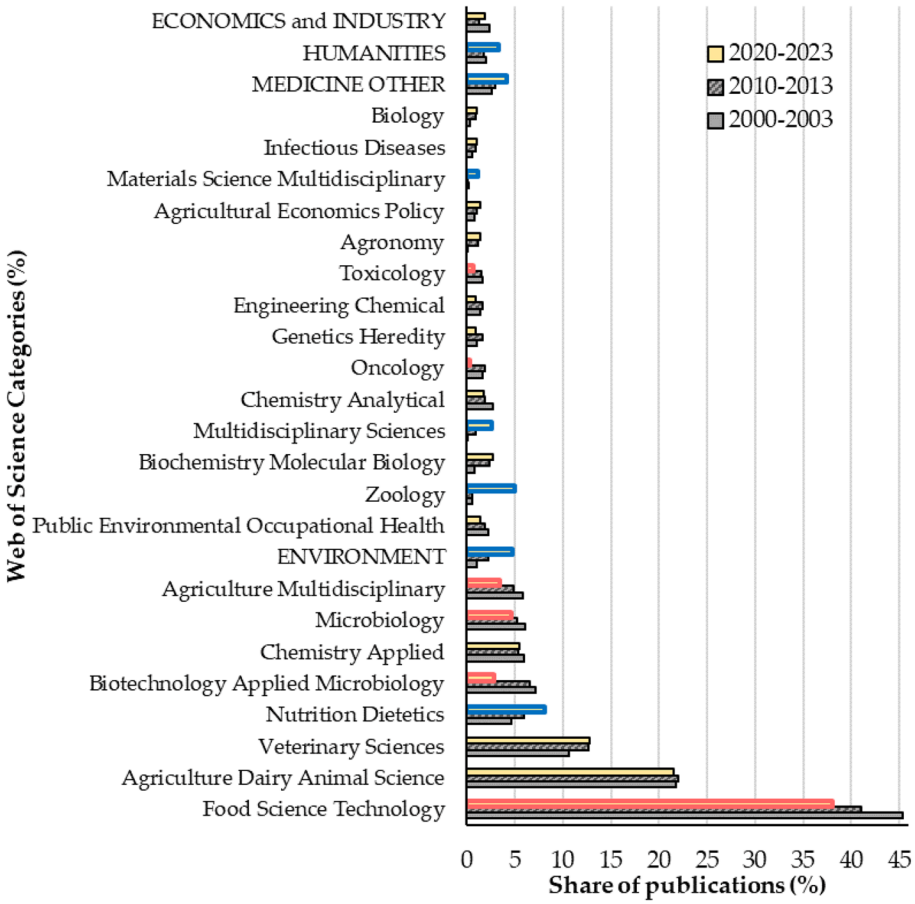


Fig. 2 Share of publications in specific areas of Web of Science in the field of meat currently, 10, and 20 years ago. Areas with a decreased contribution are traced in red, and the blue border means an increase in the share of publications. Titles of blocks with united Web of Science directions are capitalised

Thematic areas of research in the field of meat in 2013 and 2023

When analysing the main areas of research within the leading Web of Science categories publishing research in the field of meat, attention is drawn to approximately the same thematic structure of publications directly related to meat published in various Web of Science categories (Fig. 3). Works in different categories could be grouped, with minor variations, into major sectors covering raw meat and meat product quality, safety, storage and preservation, diet (including consumer preferences and health effects), industry development as a whole, and work on developing a variety of meat

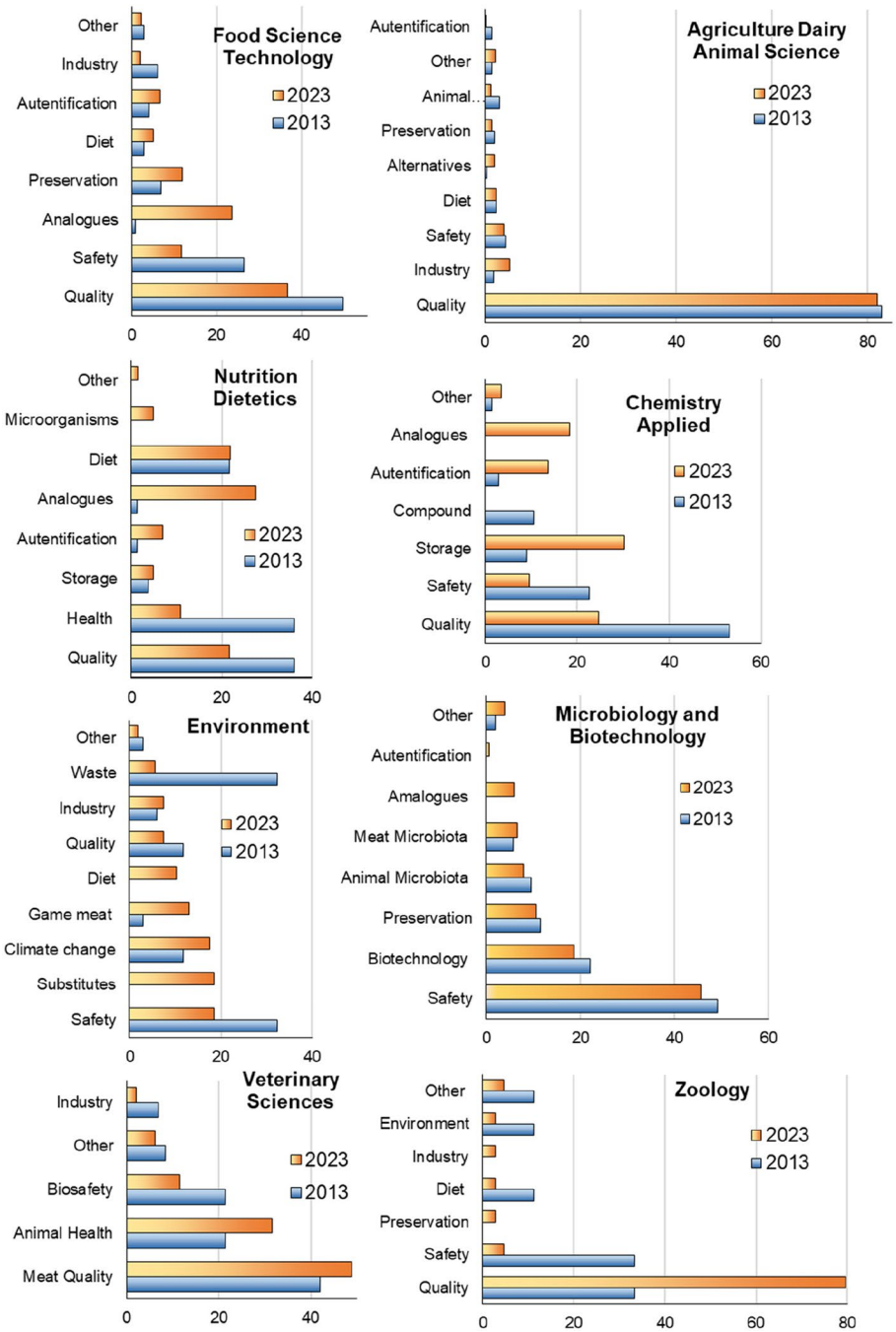


Fig. 3 Main areas of meat research in related Web of Science directions in 2013 and 2023

analogues and substitutes, including cultured meat obtained from cell cultures.

The main area of research in meat studies of almost all Web of Science directions except for environmental sciences and microbiology is meat quality (Fig. 3). Articles on meat animal productivity and meat quality make up more than 80% of publications in the direction of Agriculture Dairy Animal Science. The share of publications on meat quality has increased in Veterinary Sciences and Zoology, especially sharply in Zoology (from 33.3% up to 79.6%). On the contrary, a noticeable decrease in the share of publications related to meat quality (by 13.3–28.5%) was revealed in directions of Food Science Technology, Nutrition Dietetics, and Chemistry Applied. The most likely explanation for these changes is the movement of a significant portion of work on meat quality into areas related to livestock production.

Furthermore, the percentage of publications in the field of meat safety decreased significantly in the areas of Food Science Technology, Chemistry Applied, and the group Environment by 13.0–14.7%, as well as by 9.9% in Veterinary Sciences and by 28.7% in Zoology. In the Nutrition Dietetics direction, the publications on health and biosafety have decreased by 28.7%. There was also a decrease in the share of publications in Microbiology and Biotechnology Applied Microbiology.

Along with these changes, an obvious expansion of work on meat authentication was presented mainly in Food Science Technology, Chemistry Applied, and Nutrition Dietetics. There was also a noticeable increase in the contribution of publications (by 10.1%) concerning the health indicators and physiological characteristics of farm animals in the meat sector in the direction of Veterinary Sciences, as well as research on meat from wild and rarely consumed animals in the field of environmental sciences (by 10%). Interestingly, in the group of areas related to the environment, the percentage of work on processing meat waste decreased sharply (by 26.8%).

We have identified the topic of meat substitutes and analogues as a separate group since a pronounced surge in the number of publications in product meat-related Web of Science directions has been detected in this area. Thus, the share of publications on meat substitutes and cultured meat jumped over 10 years by 26.3 and 28.3% respectively in the areas of Nutrition Dietetics, and Food Science Technology and by 18.3–18.5% in areas related to chemistry and the environment (Fig. 3). It is quite natural that publications concerning meat substitutes are encountered only in minor quantities in areas related to raising animals.

Currently (2020–2023), a significant proportion of publications (7.6% or 792 publications out of 10,364) are works related to various meat substitutes and analogues. Just 10 years ago (2010–2013), the share of such publications was only 0.3%, namely 14 articles out of 4405 with the word "meat" in the title. Such research was often a reflection on the future of meat (Chiles, 2013; Goodwin & Shoulders, 2013; Mattick & Allenby, 2013). At present, both technologies of meat analogues and consumer preferences are widely investigated and carefully worked out.

VOSviewer text mapping of the articles with "meat" in the title

VOSviewer text mapping of the articles with "meat" in the title using the OpenAlex application programming interface shows that in both 2013 (3429 documents) and 2023 (5207 documents) the main clusters of terms extracted from abstracts and publication titles, largely coincide (Fig. 4). In 2013 studies, 4 clusters were identified, including terms repeated more than 10 times. The first two clusters are close in terms of the number of terms and correspond to areas of research in the field of meat quality and meat safety (220 and 232 terms, respectively) (Fig. 4, a). Both clusters are often combined with the term "gene," which corresponds to the influence of the genotype of meat animals on meat quality and carcass performance, on the one hand, and the presence of antibiotic resistance genes and pathogenicity factors in meat microbiota. The third largest cluster (113 terms) covers terms related to meat properties (physical, chemical, and sensory), mainly related to extending shelf life. The final cluster includes 55 terms in the areas of diet and nutrition, consumer preferences and consumer health effects, including various risks, closely related to the safety cluster.

In 2023, terms occurring more than 10 times were divided into four main clusters, as in 2013, with the addition of one small cluster including only eight terms related to animal health (immunity, blood parameters, digestive health and microbiota) (Fig. 4, b).

The first Cluster, including 440 items, covers research related to meat quality and growth performance of different agricultural animals including carcass and meat traits when keeping animals in various conditions, with different diets and supplements. The weight of the carcass, colour, metabolite profile and other indicators of meat are taken into account, both sensory and ensuring the greatest safety of the resulting product. This Cluster 1 is closely related to Cluster 3 Properties and Preservation, which covers various properties of meat, both chemical and physical, depending on storage and processing conditions.

Cluster 3 also includes a significant portion of items related to meat analogues located closer to Cluster 2, related to diet, consumer preferences and health effects. In Cluster 2, the most common terms are risk

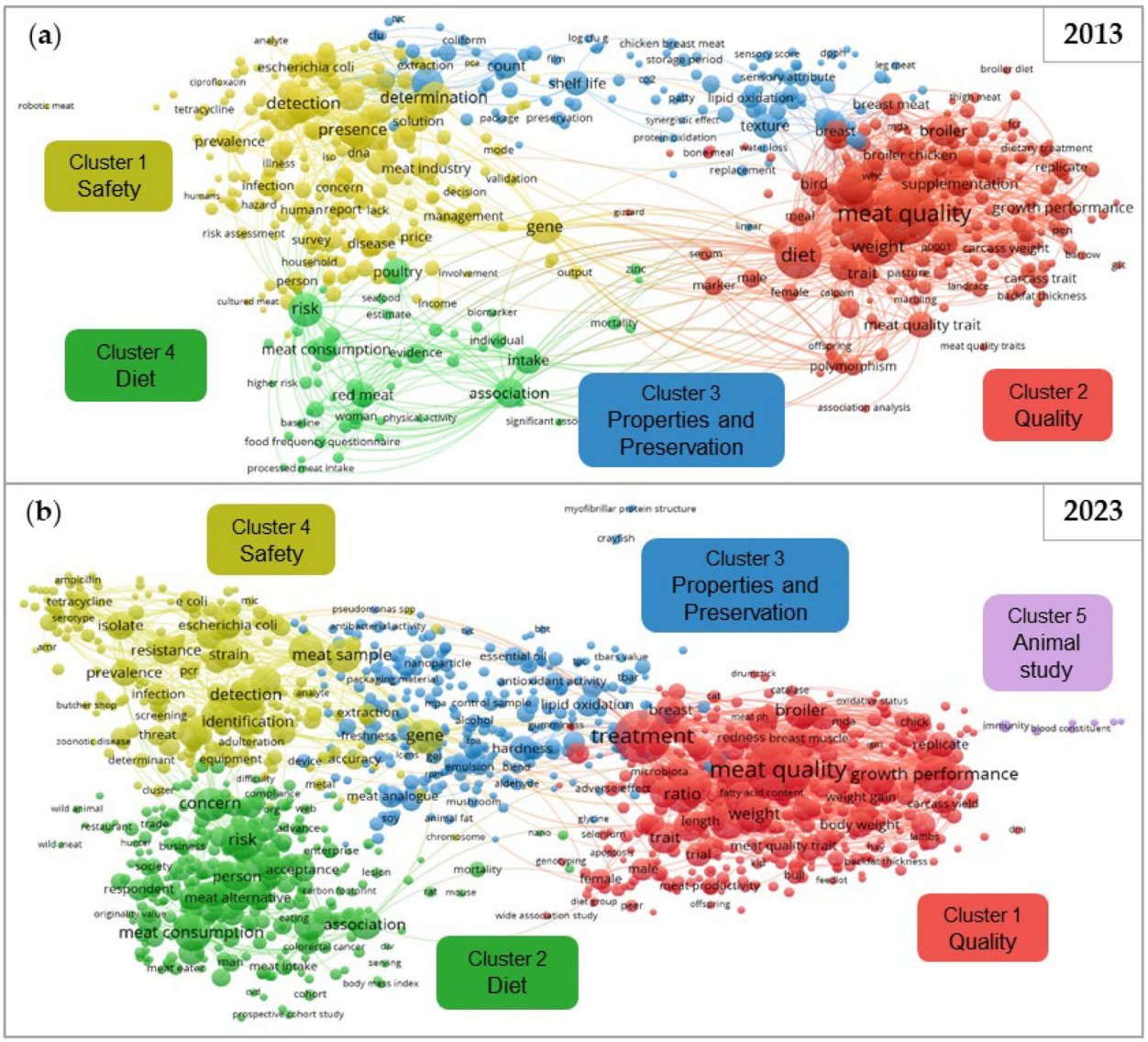


Fig. 4 VOSviewer 1.6.20 text mapping of the title and abstract terms from publications with "meat" in the title in 2013 and 2023 (using OpenAlex)

and concern, associated with various properties of meat and closely intertwined with Cluster 4, covering safety and biosafety. The overwhelming majority of research in this area of safety is related to microbiological safety and the presence of antimicrobial resistance in detected microorganisms and, at the same time, is closely related to research aimed at protecting meat from spoilage and the development of pathogenic and potentially dangerous organisms. The term "gene" connects Cluster 1 and Cluster 2 with many terms, implying both studies of the genotype of meat breeds of animals and the microbiota of meat, which carries pathogenicity factors and antibiotic resistance genes.

The percentage contribution of individual clusters has changed somewhat compared to 2013. Thus, the share of safety research was only 18.4% in 2023, while in 2013 this sector was the leading sector and covered 37.4% of recurring terms. In turn, it was noted that if in 2013 the number of terms in the "Diet" cluster was 8.9% of the total number of terms, then in 2023 this sector accounted for 27.4% of the total number of terms repeated more than 10 times. The main groups of terms in this cluster are associated with the terms "risk", "concern", and "meat consumption". The term "risk" has the greatest number of connections with terms from the Safety cluster related to the contamination of meat by pathogenic

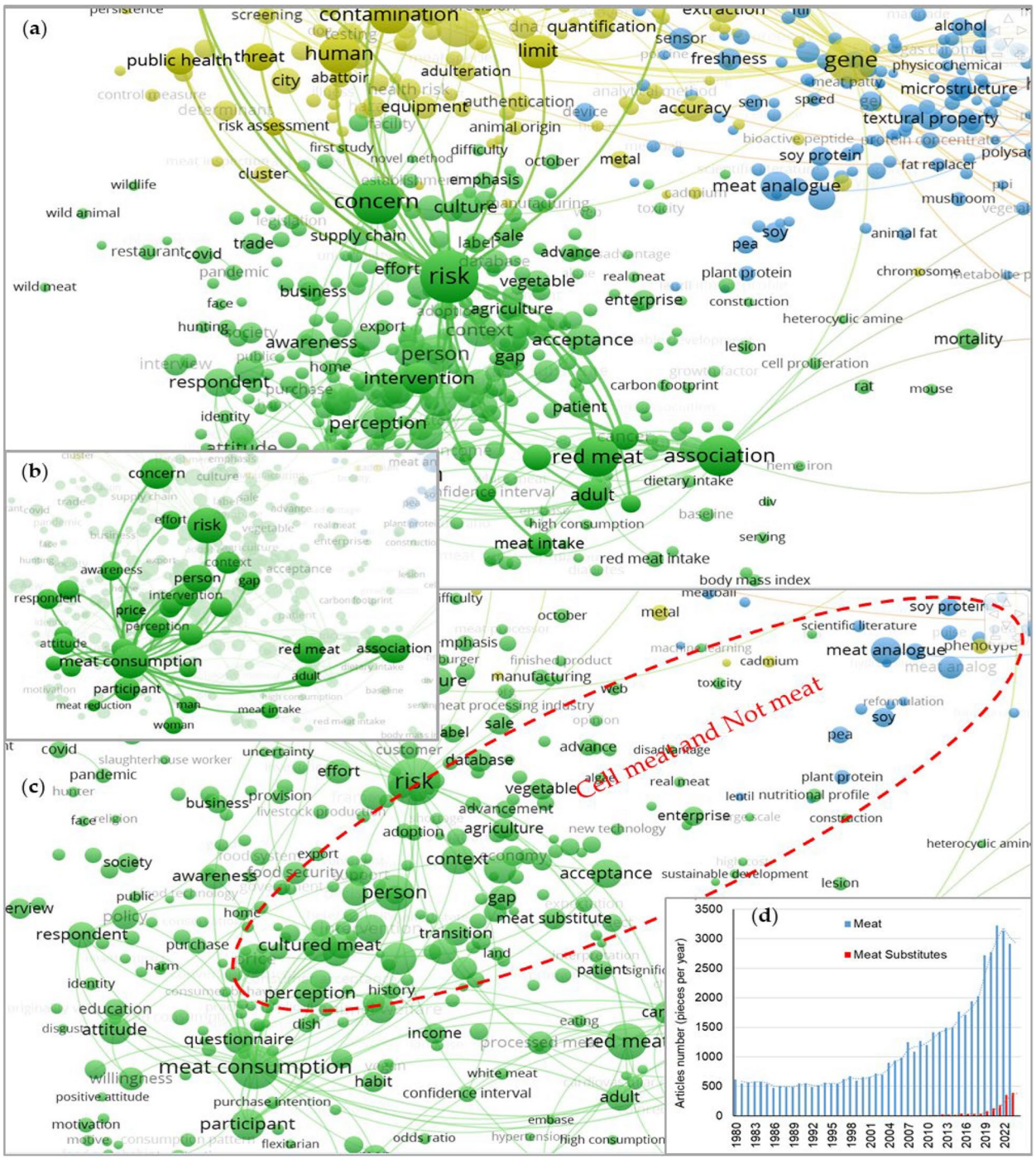


Fig. 5 Main groups of title and abstract terms of the Diet cluster in 2023, VOSviewer text mapping, OpenAlex. (**a**) Connection with the "security" cluster through the term "risk"; (**b**) The group of terms related to meat consumption; (**c**) The group of terms in the field of meat substitutes and analogues; (**d**) Total number of publications per year including "meat" and all variants of meat substitutes and analogues in article titles, from 1980 to 2023

microorganisms (Fig. 5, a, b). At the same time, in the Diet cluster, a group of terms related to analogues and meat substitutes and their perception by consumers is identified (Fig. 5, c). The total share of publications on all types of meat substitutes and analogues among the total number of articles with the term "meat" in the title

has been growing steadily in recent years. Publications in this area began to appear en masse only over the last decade, while in previous years they were sporadic. In the total number of publications directly related to meat, the sector of meat analogues has stood out in recent years, accounting for 13.2% of the total number of publications with the word "meat" in the title in 2023 (Fig. 5, d) and almost reaching the level of publications on meat in 1980–1990s. In the first four months of 2024, the share of publications on meat alternatives in the total number of publications with "meat" in the title was already 15.7%.

Mapping the main terms included in the titles of articles along with the term "meat" shows a more pronounced structure of publications. In both periods, sectors were aggregated into two groups: agriculture and animal-oriented studies in meat production (the influence of various factors associated with keeping animals on the quality of meat and the impact of genotype on the quality of meat) and the study of meat as a food product (properties of the product, diet and consumer preferences, meat product authentication) (Fig. 6 a, b). At the same time, terms in the field of animal husbandry are more clearly separated in the titles of publications by animal species and most often related to each other by the terms "supplementations" (dietary), "growth performance", and "carcass" properties. Mapping by terms found in publication titles reveals a distinct cohort of terms related to meat substitutes. The "meat analogues" cluster stands apart from other terms.

Thus, based on the analysis of abstracts of publications from the Web of Science database with the word "meat" in the title, and mapping of terms of similar publications extracted using the OpenAlex API for 2013 and 2023, the main areas of research in the field of meat, as well as trends, were identified. If in 2013 the bulk of meat research was focused mainly on its quality and safety, then in 2023, there was a decline in the share of research in the field of meat safety with an increase in the percentage of publications related to diet, consumer preferences, methods of meat preservation and the development of alternative products to meat. In the following sections, we will consider the specific achievements in the field in revealed areas and emphasise the changes that have occurred over 10 years.

Main areas of meat research now and ten years ago

Meat quality

Research in the field of meat quality is dominant among all other studies related to meat, and at the same time is closely intertwined with remaining areas, since meat quality determines its nutritional and sensory characteristics directly connected with consumption, as well as properties ensuring its safety and biosafety. The attention of researchers in the field of meat quality was focused primarily on the physicochemical and sensory properties of raw and processed meat, which contribute to increasing its tenderness and oxidative stability, improving taste, and delaying biochemical spoilage during storage. A significant share of publications included studies on factors associated with raising carcass traits and meat quality of animals.

In 2013, attention was paid to the influence of breed, genotype (Alvarez et al., 2013; Fontanesi et al., 2013; Nonneman et al., 2013), age, sex, castration, level of social dominance, pregnancy, animal growth rate, diet, feeding regime, replacements of some diet ingredients for other ones, various dietary supplements, special conditions of keeping (fasting, water restriction, transportation conditions, exposure to stress factors, the influence of monochromatic light, and even the effects of heat stress on embryos (Kim et al., 2013b; Loyau et al., 2013), as well as the time and method of slaughter, including the stunning, on the post-mortem quality and storage of meat. Attempts have been made to predict the quality of the carcass using ultrasound examination of live animals (Ayuso et al., 2013). In the resulting product, meat indicators related to its nutritional value and preservation were studied, including biochemical indicators (vitamin D, lipids, fatty acids, α-keto acids, and mineral elements, such as selenium) with an emphasis on the development of research methods and certain indicators of meat. A significant part of the studies was devoted to flavour chemistry and oxidative processes in meat as indicators of both, meat quality and meat spoilage, including the influence of pH, salts, herbal additives and extracts, mainly providing an antioxidant effect. At the same time, research was directed at optimal methods for quickly detecting meat spoilage and searching for molecular markers for meat quality (Dissing et al., 2013; Sevane et al., 2013). A separate layer of work consisted of studies of various indicators of the meat quality of non-traditional and rarely consumed animal species in meat agriculture (camel, Muscovy duck, nutrias, emu). There were also works in the field of cooking, studying the effect of the cooking method and the influence of various indicators of meat on the quality of cooked food and its taste.

In 2023, with an increase in the number of publications, the coverage of various aspects of meat quality research has expanded. The number of dietary supplements studied that influence carcass performance and meat quality has increased significantly. Thus, in 2023 alone, more than 230 types of additives to the diet of meat animals were evaluated (more than 90 in 2013) in publications indexed in the Web of Science. The effect of additives was studied in 2013 on 20 breeds and species of animals, and

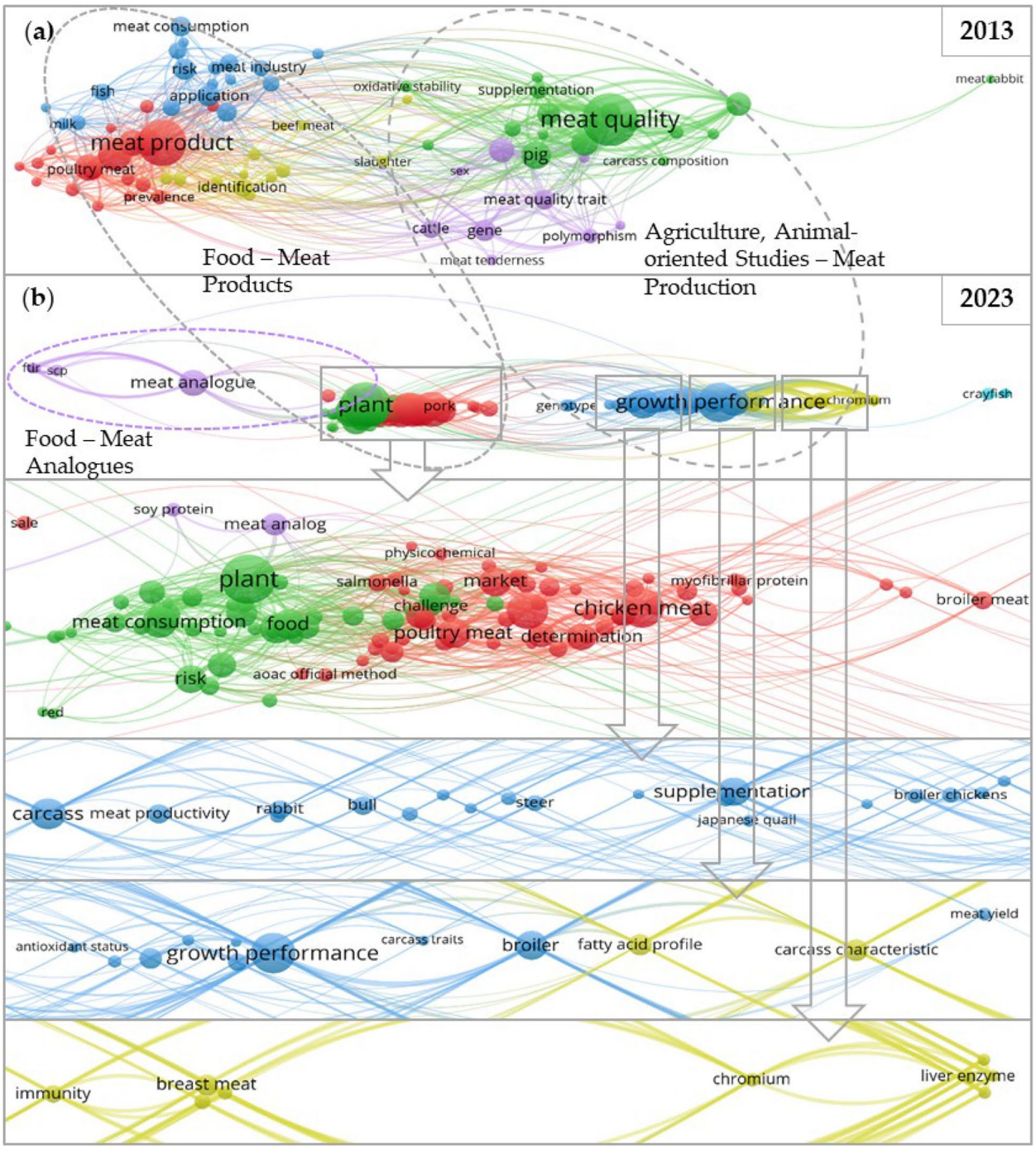


Fig. 6 VOSviewer mapping of title terms in meat research, OpenAlex. (**a**) 2013; (**b**) 2023, the new "meat analogues" cluster has appeared

in 2023 this number has grown to 45. The most actively used supplements were a variety of herbal additives and extracts, by-products and waste from processing industries, and bioactive additives of various origins.

In 2023, the number of studies on the effect of probiotics and fermented foods in animal feeding on meat quality has significantly increased, and the list of plants, their parts and extracts used as dietary supplements has also largely expanded. Compared to 2013, some works on enzymes, seaweed, insects, and their larvae (in poultry and rabbit diets) effects have appeared. The list of animals, on which the influence of various additives has

been studied, also widened. More detailed comparative information on the supplements studied in 2013 and 2023 is provided in Additional file 1. The main focus among the meat quality indicators, both in 2013 (El-Senousey et al., 2013; Parveen et al., 2013; Tomazin et al., 2013) and in 2023 (Ali et al., 2023; Pestana et al., 2023; Wang et al., 2023i), concentrated on meat tenderness and antioxidant properties to mitigate reactive oxygen species.

The increase in the number of dietary supplements and animal breeds studied has not been the only change in meat quality research over the past 10 years. Huge progress in this direction is associated with the development and sophistication of research methods (Alves et al., 2023; Chen et al., 2013c). So, the analyses of volatile, metabolomic, lipidomic and proteomic profiles of meat from various animal breeds (under different feeding regimes and other conditions) and meat during storage were actively used to assess the quality, safety and shelf life of meat in 2023 (Chang et al., 2023; Yang et al., 2024; Chen et al., 2023b). Some genotype characteristics (individual genes, genomic polymorphisms, transcriptome profiles) influencing significant indicators of carcass and meat quality are being studied much more widely in 2023 (Alsoufi et al., 2022; Hernández-Herrera et al., 2023; Safaa et al., 2023).

Because meat products are often adulterated due to their higher cost, research into developing methods for detecting adulteration has increased in recent years. Development of molecular genetic, spectrometric and other methods for analysing is the observed progress in the field of meat authentication. In 2013, work in this direction was quite sporadic and mainly used standard PCR, first-time PCR, liquid chromatography and infrared spectrometry (Table 1). In 2023, multiplex PCR became the standard method, and new, more accurate and faster analysis methods have already been developed (Tables 2 and 3). The widespread use of multiplex PCR has made it possible to detect meat adulteration more effectively, reveal various inclusions in the product in a single analysis, and control the harvesting of rare and endangered animals for meat. The use of new methods of droplet digital PCR (Floren et al., 2015) and isothermal polymerase spiral reaction (PSR) (Gupta et al., 2017) have become completely new approaches. The use of new methods has made it possible to develop rapid and highly reproducible methods for accurately detecting various types of meat and reducing the limits of quantification (LOQ) and detection (LOD) (Floren et al., 2015; Nesvadbova et al., 2023). These advances have taken meat product analysis to a whole new level, allowing for detecting subtle differences in product composition. Among spectrometric

Table 1 Methods of meat authentification in 2013

Method	Target	Reference
DNA-based methods		
Polymerase chain reaction (PCR)	Chicken	Karabasanavar et al., 2013
PCR	Beef, chicken, and turkey	Ulca et al., 2013
PCR	Gender origin of meat from cattle, sheep, and goat	Gokulakrishnan et al., 2013
Real-time PCR	Seagull meat in meat mixtures	Kesmen et al., 2013
Real-time PCR	Pork meat in processed meat products	Soares et al., 2013
Semi-nested multiplex PCR; multiplex PCR using truncated primers	Chicken, beef, pork and mutton species in meat products	Zhang, 2013
PCR followed by a High-ResolutionMelting (HRM) analysis	Buffalo	Sakaridis et al., 2013
Alkaline lysis method of DNA extraction and species specific PCR	Buffalo	Girish et al., 2013
Chromatography		
Ultra-performance liquid chromatography (UPLC) using myoglobin as a marker	Pork meat in beef	Giaretta et al., 2013
Spectroscopy		
UV-visible (UV-vis), near-infrared (NIR) and mid-infrared (MIR) spectroscopy, coupled with chemometric techniques	Minced beef adulteration with turkey meat	Alamprese et al., 2013
Near-infrared (NIR) hyperspectral imaging.Determination of citrate synthase activity in meat exudate, spectrophotometric method	Minced lamb	Kamruzzaman et al., 2013
Determination of citrate synthase activity in meat exudate, spectrophotometric method	Adulteration of fresh chicken meat, substitution with frozen and thawed meat	Šimoniová et al., 2013
Isotopic ratio mass spectrometry	Inclusion of poultry offal meal in the diet of meat-type quails	Sernagiotto et al., 2013

Table 2 DNA-based methods of meat authentification in 2023

Method	Target	Reference
DNA-based methods (systematic review)	Game and less common meat species	Adenuga et al., 2023
PCR	Broadhead catfish (*Clarias macrocephalus*), African catfish (*Clarias gariepinus*), and black eel-tail catfish (*Plotosus canius*)	Benjakul et al., 2023
PCR	Frog meat (specificity against common halal meat sources such as beef, chicken, shrimp, squid, and mackerel)	Haryono et al., 2023
Microarray chip PCR-directed microfluidic lateral flow strip (LFS) device	Beef adulterated with chicken, duck, and pork	Wang et al., 2023a
Real-time PCR	Different meat species in meat products marketed as beef	Özlü et al., 2023
Duplex PCR	Cattle and pork	Barido et al., 2023
Triplex real-time PCR	Meats and antlers from sika deer (*Cervus nippon*) and red deer (*Cervus elaphus*)	Liu et al., 2023b
Multiplex-PCR	Deer, cow, sheep, pig and horse	Wang et al., 2023f
Multiplex-PCR	*Columba livia, Corvus moneduloides, Gallus gallus, Coturnix japonica, Phasianus colchicus, Struthio camelus*, and *Meleagris gallopavo* meats	Rajaei & Doosti, 2023
Multiplex-PCR	Cattle and buffalo meat	Karabasanavar et al., 2023
Multiplex-PCR	Bovine, chicken, porcine, dog, and rat ingredients in beef products	Wibowo et al., 2023
Multiplex-PCR using a polydimethylsiloxane microfluidic device	Beef, chicken, pork, and duck	Yu et al., 2023a
Direct quantitative real-time PCR (qPCR)	Pork in processed meat products	Kusnadi et al., 2023
qPCR	Rat in meat	Ji et al., 2023
TaqMan multiplex qPCR (multiplex real-time polymerase chain reaction (mqPCR))	Meat products (review)	Hossain et al., 2023
High-resolution melt analysis (HRMA)	Commonly used meat species	Jafar et al., 2023
Droplet digital PCR (ddPCR)	Pork in cattle	Milli et al., 2023
ddPCR	Beef (*Bos taurus*) and lamb (*Ovis aries*)	He et al., 2023b
ddPCR	Buffalo substitution in 'Haleem'	Kumar et al., 2023a
qPCR and ddPCR	Dominant meat species (pork, chicken and beef) in samples of 2- and 3-component mixtures and meat products	Nesvadbova et al., 2023
DNA-metabarcoding	Different taxa	Denay et al., 2023
Real-time fluorescent loop-mediated isothermal amplification (LAMP)-microfluidic assay	Pork, beef, sheep and duck in foodstuffs	Zhang et al., 2023a
Real-time enzymatic recombinase amplification (real-time ERA)	Horse-, donkey- and pig-related meat products	Zhou et al., 2023
Integrating microneedle DNA extraction to hand-held microfluidic colorimetric (visual) LAMP system	Goat meat, sheep meat, pork meat, chicken meat, donkey meat, and duck meat	Xiao et al., 2023
Recombinase polymerase amplification (RPA) combined with CRISPR/Cas12a technology	Chicken, duck, beef, pork and lamb	Liu et al., 2023f
RPA combined with CRISPR/Cas12a	Beef, mutton, pork, chicken, and duck	Ding et al., 2023
Isothermal polymerase spiral reaction (PSR)	Buffalo (*Bubalus bubalus*)	Jawla & Chatli, 2024
PSR	Goat (*Capra hircus*)	Shree et al., 2023
PSR	Pig	Danawadkar et al., 2023
Dual-recombinase-aided amplification (dual-RAA) technology and visual multiplex lateral flow strips (MLFSs)	Duck- and bovine-derived, porcine- and bovine-derived, duck- and ovine-derived, and porcine- and ovine-derived meat	Cao & Song, 2023

methods, liquid chromatography-high-resolution mass spectrometry and infrared spectroscopy are actively developing (Table 3). An important aspect is the development of devices for simple and rapid DNA extraction and identification (Hu et al., 2023; Wang et al., 2023a). The progress in simplifying and facilitating analyses guarantees widespread adoption of the developed methods and the potential to have a significant impact on the meat industry as a whole improving meat quality and safety.

The research in 2023 also highlights the spiritual quality aspects of meat that satisfy religious needs for halal

Table 3 Other methods of meat authentification in 2023

Method	Target	Reference
Gas chromatography-ion mobility spectrometry (GC-IMS)	Discriminating donkey meat	Man et al., 2023
Glycopeptide analysis by UPLC-QTOF-MS	Pork, beef, mutton, chicken, duck and turkey	Tai et al., 2023
Liquid chromatography-high-resolution mass spectrometry (LC-HRMS), LC-Orbitrap HRMS	Pork in Tuna Meat	Suratno et al., 2023
Non-targeted UHPLC-Orbitrap HRMS	Dog meat in beef meatballs	Windarsih et al., 2024
Untargeted UHPLC-HRMS	Beef and pork	Maritha et al., 2023
LC-HRMS followed by protein identification using Spectrum Mill software and multiple reaction monitoring (MRM), liquid chromatography coupled to triple quadrupole mass spectrometer (LC-TQ)	Heat-stable peptide markers of chicken and rabbit; distinguishing liver tissue from skeletal muscle	Stachniuk et al., 2023
LC-Orbitrap HRMS and Chemometrics	Authentication of Beef Meats	Windarsih et al., 2023
Gel-eluted liquid fraction entrapment electrophoresis (GELFrEE) coupled with MALDI-TOF mass spectrometry (MS)	Adulteration of water buffalo meat with pork	Banerjee et al., 2023
LC–MS/MS	Alfalfa, buckwheat, broad bean, chia, chickpea, coconut, egg, flaxseed, hemp, lentil, lupine blue, maize, milk, pea, peanut, potato, pumpkin, rapeseed, rice, sesame, sunflower, soy, and wheat in meat products	Spörl et al., 2023
Fourier Transform Infrared Spectroscopy (FTIR)	Lard adulteration in cow, lamb, and chicken	Siddiqui et al., 2023
Near-infrared (NIR) and near-infrared hyperspectral imaging (NIR-HSI)	Adulteration of alpaca (*Vicugna pacos*) meat with pork, chicken, and beef	Cruz-Tirado et al., 2024
NIR spectroscopy and chemometrics analysis	Goat	Cozzolino et al., 2024
NIR and electronic nose	Adulterated lamb meat	Jia et al., 2024
Visible-near infrared hyperspectral imaging (Vis–NIR-HSI)	Pork in beef, pork in lamb and pork in chicken	Dashti et al., 2023
^{1}H NMR spectroscopy combined with chemometrics	Pork and duck in minced beef	Leng et al., 2023
Combining hyperspectral imaging (HSI) technique with transfer learning	Starch in minced chicken meat	Yang et al., 2023b
Immunochromatographic analysis (ICA)	Pork	Hendrickson et al., 2023
Lateral flow device (LFD)	Pork adulteration	Raja Nhari et al., 2023
Differential scanning calorimetry (DSC)	Beef, pork, rabbit, and chicken	Nugrahani & Aditya, 2023
E-nose	Beef, chicken, and pork	Putri et al., 2023

products and relate to both the authentication of prohibited meat types (Raja Nhari et al., 2023) and methods of stunning/slaughtering animals (Abd El-Rahim et al., 2023; Govindaiah et al., 2023).

Meat nutritional composition, benefits for human health, and the possibility of using meat from alternative species (such as red deer, fallow deer, rabbit, horse, pigeon, ratites (mainly ostrich), wild boar, and *Caiman yacare* studied in 2013 (Morais et al., 2013; Poławska et al., 2013; Sales & Kotrba, 2013) in comparison with conventional meat are in focus in 2023 as well. Game meat is also being studied as a sustainable alternative for consumption, for example, yellow anaconda and bullfrog (Leiva et al., 2023; Magalhães et al., 2023).

The meat quality and freshness field shows significant advancements in the search for biomarkers and the development of biosensors for rapid and high-quality detection. Researchers have made progress in several areas, including applying transcriptomic and metabolomic analysis to identify key genes involved in odour formation (Gai et al., 2023). Additionally, they have developed highly sensitive sensors to detect compounds with umami taste (Liu et al., 2023d) and identified new umami peptides (Wang et al., 2023d). Studying the conformational structures and gel properties of myofibrillar proteins (Wang et al., 2023b) and developing methods for determining meat proteins (Alves et al., 2023; Huang et al., 2023) have also been important areas of research. The electronic nose (E-nose), eye (E-eye), and tongue (E-tongue) are currently widely used for the fastest and most accurate assessment of significant indicators (Munekata et al., 2023).

Novel sensing systems have been developed to assess meat freshness (Duan et al., 2023; Geng et al., 2023; Wu et al., 2023a), while determination of lysine-derived markers for protein carbonylation (Wang et al., 2023e), analysis of ammonia (Deng et al., 2023) and hydrogen sulfide (Li et al., 2023b) content, and lipid oxidation in meat (Katsanidis & Zampouni, 2023) enable the determination not only of quality indicators but also the prediction of shelf life and assessment of meat product safety. Special films allow for receiving visual and easily

interpretable results, making it possible to assess meat quality and freshness (Huang et al., 2024; Khan et al., 2023) quickly.

Meat quality issues are inextricably linked to ensuring meat safety and the need to control individual compounds, as well as opportunistic and spoilage microorganisms, which contribute to producing potentially hazardous compounds and spoilage markers.

Safety and biosafety

In 2013, the research on meat safety and biosecurity focused primarily on detecting and quantifying hazardous chemicals and pathogenic microorganisms that cause foodborne illness outbreaks. Most articles published in the Web of Science database in this area focused on the microbiological safety of meat and products.

The main concerns were related to the presence of foodborne pathogens such as *Listeria, Campylobacter, Salmonella, Aeromonas, Enterococcus*, coagulase-positive *Staphylococcus, Clostridium botulinum, Clostridium difficile, Helicobacter*, shiga toxin-producing *Escherichia coli, Yersinia enterocolitica, Mycobacterium*, and fungal microbiota (Anjum et al., 2013; De Cooman et al., 2013; Dmowska et al., 2013; Dorn-In et al., 2012; Van Damme et al., 2013). Additionally, parasitic protozoa (Gencay et al., 2013) and tapeworm cysticerci (Cayo et al., 2023) contribute significantly to the potential hazards of meat consumption. Fewer studies focused on detecting viruses in meat (Di Pasquale et al., 2013).

Another concern in 2013 was the formation of biofilms, particularly by *Salmonella*, in meat processing environments (Wang et al., 2013). Furthermore, publications from 2013 presented works on selecting and standardising methods for detecting and rapidly identifying dangerous microorganisms in meat (Anjum et al., 2013; Delibato et al., 2013; Rohonczy et al., 2013). One notable development was the creation of a multiplex fibre optic sensor that successfully detected each of three pathogens grown in a mixture—*Salmonella, E. coli*, and *Listeria* (Ohk & Bhunia, 2013).

Of particular concern was the role of meat as a genetic reservoir of transferable antibiotic resistance (Yurdakul et al., 2012; Jahan et al., 2013; Lerma et al., 2013). Regarding the possible spread of microbial resistance, studies of *E. coli* integrons from poultry meat, which are genetic elements implicated in the acquisition and expression of antimicrobial resistance genes, are interesting (Soufi et al., 2013). In reducing the danger of meat products, it is worth noting the developments in ameliorating aflatoxicosis in broiler chickens receiving mouldy feed in the diet using the microbial culture *Bacillus subtilis* (Fan et al., 2013).

Among chemical contaminants, which are predominantly undesirable residues of organic substances, the presence of polycyclic aromatic hydrocarbons (Olatunji et al., 2013), biogenic amines (Lázaro et al., 2013), residues of antibiotics of the quinolone group, anti-inflammatory drugs, such as caprofen (Chen et al., 2023c), feed additives (ractopamine) was detected (Li et al., 2013; Silfrany et al., 2013). The possible presence of trace elements and heavy metals (Chen et al., 2013b) mycotoxins, sulfamethazine, volatile N-nitrosamines, as well as nitrate and nitrite leading to the formation of N-nitroso compounds, peroxide, perchlorate anions, and meat radioactivity was also discussed. Likewise, the use of blood-based binding agents in meats, which contain thrombin (Grundy et al., 2013), raises serious concerns. In the field of chemical safety of meat, research on developing methods for quick and qualitative assessment of the content of certain indicators, for example, synthetic dyes (Sun et al., 2013; Zou et al., 2013), antibiotics (Douny et al., 2013), and volatile N-nitrosamines (Huang et al., 2013) was also carried out.

A large proportion of publications in 2023 are related to the development of more efficient, accurate and rapid methods for detecting pathogenic microorganisms (Lamas et al., 2023; Vishnuraj et al., 2023). Thus, the Helix loop-mediated isothermal nucleic acid amplification method recently developed by Mao et al. (2018), was applied for ultrasensitive detection of *Listeria monocytogenes* in chicken meat (Prasad et al., 2024). Additionally, meat biosecurity research in 2023 is more focused on meat preservation (Osaili et al., 2023; Taboada et al., 2023) than in 2013. Efforts are made to reduce pathogen levels in meat when stored under certain conditions. The possibility of direct effects on parasites is also under interest, for example, by inactivating nematode larvae with pulsed electric fields (Abad et al., 2023). The advancements in molecular and spectrometric methods made in recent years have significantly affected meat safety and security issues. The investigations in the field of meat safety moved in 2023 to the last place among other clusters as shown in Fig. 4. However, a large number of studies are still devoted to meat safety. There has also been an increase in the number of reports of pathogen biofilms in watering equipment (Buder et al., 2023) and production environments (Russell et al., 2023; Voronina et al., 2023; Yang et al., 2023c). The spread of antimicrobial resistance among microorganisms found in meat continues to be a major concern (Aiyegoro et al., 2023; Conceição et al., 2023; Motallebirad et al., 2023; Xedzro et al., 2023; Yang et al., 2023a), potentially associated with risk for human health (Locus et al., 2023; Ndiana et al., 2023; Swanenburg et al., 2023). Notably, a significant increase has been observed in research focused on the presence of viruses

in meat compared to 2013 (Locus et al., 2023; Ndiana et al., 2023; Swanenburg et al., 2023). Specifically, studies have investigated the African swine fever virus (Ladoși et al., 2023; Okwasiimire et al., 2023) and hepatitis E (Akpoigbe et al., 2023; Di Cola et al., 2023). Moreover, a notable connection has been established between bovine leukaemia and human breast cancer by de Quadros et al. (de Quadros et al., 2023), which raises concerns about the risk of zoonotic infections spreading through meat consumption. In addition, game meat has been identified as another potential source of zoonotic infections caused by bacteria, viruses, and parasites (Tumelty et al., 2023).

In 2023, research continues to focus on developing approaches for detecting hazardous compounds in meat (Li et al., 2023c; Marggraf et al., 2023). The largest body of research on chemical contaminants in meat focuses on the methods for detecting and reducing biogenic amines (Pawul-Gruba et al., 2023; Sun et al., 2023a; Wang et al., 2024; Jastrzębska et al., 2024) and antibiotic residues (Chandrakar et al., 2023; Doyuk & Dost, 2023; Hakiem et al., 2023; Jing et al., 2023; Lin et al., 2023). A significant proportion of studies on raw and cooked meat emphasizes the presence of mutagenic and carcinogenic compounds such as heterocyclic aromatic amines (Oz et al., 2023), polycyclic aromatic hydrocarbons (Assogba et al., 2024; Huynh et al., 2023), ochratoxin A (Sharafi et al., 2023), heavy metals (Al-Sultan et al., 2023; Kamaly & Sharkawy, 2023; Xiang et al., 2023), and N-nitrosamines (Xie et al., 2023). Several residual preparations are still in the focus (Tshepho et al., 2023).

Many studies are dedicated to the detection and risk assessment of new biological threats in meat in the form of biologically active compounds. Of particular awareness is the possible use of illegal growth promoters such as selective androgen receptor modulators (SARMs) in animal rearing, which raises concerns about their misuse to increase muscle mass (Kaufmann et al., 2023), and beta-adrenergic agonists added to animal feed to improve carcass leanness (Tu et al., 2023; Yan et al., 2023). Additionally, there is ongoing research into the role of N-glycolylneuraminic acid as a specific factor in red meat that induces intestinal disease by damaging intestinal barrier function (He et al., 2023a). Furthermore, it has been shown that organic meat, although meeting regulatory limits, is significantly more contaminated with persistent organic pollutants such as dioxins, lead, organophosphate pesticides, antibiotics, mycotoxins, and other substances (Engel et al., 2023).

Preservation

The share of work devoted to the development of methods for protecting meat from spoilage remained in the same position in 2023 as in 2013 (Fig. 4). It should be noted that a detailed scientometric analysis has been published in this area by Zhang et al. (Zhang et al., 2023b). For these two reasons, we refer readers to this work and will not discuss in detail the issues of protecting meat from spoilage in our review.

The above-considered research areas of meat quality, safety, and preservation concern the properties of meat as a product. Its further consumption gives rise to a huge layer of research in nutrition and dietetics including nutritional qualities of meat, health effects, consumer preferences, and possible alternatives in the case of non-meat diets.

Diet and nutrition

Research into meat related to various diets and consumer preferences has expanded significantly in 2023 compared to 2013 (Fig. 2, Fig. 4). Investigation in this area is closely linked to meat safety. On the map of repeated terms (Fig. 5) we can see that this connection is mediated through the term "risk" and is associated with a possible negative health effect from eating meat contaminated with pathogenic microorganisms, including antibiotic-resistant bacteria, and hazardous chemical compounds, on the one hand, and the likelihood of developing certain non-communicable diseases, on the other hand. Another sector of research in this cluster directly concerns the consumption of meat, especially red meat, readiness to consume it, and factors influencing the decision made. In 2013, "meat consumption" was directly associated with the "meat quality" cluster; in 2023, such a connection is weakly expressed. In addition to this, a layer of terms related to meat alternatives stands out clearly (Fig. 5).

Meat in nutrition and dietetics ten years ago

A decade ago, research into diet and consumer preferences for meat was largely concerned with assessing risks associated with eating red (beef, lamb, pork, and game) and processed (sausages, salami, bacon, hot dogs, etc.) meat.

Much of the research on meat consumption has been devoted to clarifying the controversy surrounding the association between the consumption of red and processed meats and the risk of colorectal cancer and increased mortality. Many researchers aimed to confirm or refute this idea, while identifying and summarizing the possible causes of the potentially carcinogenic effect (Kappeler et al., 2013; Kim et al., 2013a; Miller et al., 2013). A carefully designed study by Miller et al. (Miller et al., 2013) using the National Cancer Institute database (2,022 participants, from which 416 with proximal colon cancer, 253 with distal colon cancer, and 289 cases with rectal cancer) confirmed a positive association between processed meat and proximal colon cancer risk. The

study by Egeberg et al. (Egeberg et al., 2013) revealed the association between meat animal origin and colon and rectal cancer. The higher consumption of lamb increased the risk of colon cancer, while the high intake of pork affected the risk of colorectal cancer (53,988 participants with 644 cases of colon cancer and 345 cases of rectal cancer). However, replacing red meat with fish significantly reduced the risk of colon cancer, but replacing it with poultry had no effect. The reduction of cancer risk with greater intakes of unprocessed poultry was an unexpected finding of Miller et al. (Miller et al., 2013) research team. The authors attributed this result to the lack of heme, which can stimulate the production of nitroso-compounds in the intestines, as well as other dietary and lifestyle features of people who eat more poultry. Among the most likely causes of colorectal cancer are proteins in the meat, heme iron, N-nitroso compounds, and heterocyclic aromatic amines (Kim et al., 2013a), of which some refer to the content of meat (e.g. protein, heme) and other compounds are generated by the cooking process (e.g. N-nitroso compounds, heterocyclic amines). Studies by Helmus et al. (Helmus et al., 2013) confirm the connection between red meat-derived heterocyclic amines and polycyclic aromatic hydrocarbons with carcinogenesis.

However, colorectal cancer is not the only cancer associated with meat consumption. Thus, a positive association of red meat consumption with the risk of lymphoid cancer (De Stefani et al., 2013) and acute myeloid leukaemia (Yamamura et al., 2013) was revealed. In turn, the low consumption of red and processed meat and higher fish intake may reduce the risk of oesophagal squamous cell carcinoma (Salehi et al., 2013).

In 2013, studies were also conducted on the effect of increased meat consumption on the risk of other significant diseases. According to several researchers (Ericson et al., 2013; White & Collinson, 2013), the consumption of red and (or) processed meat was associated with an increased risk of type 2 diabetes (T2D), being possibly associated with advanced glycation and lipoxidation end-products (White & Collinson, 2013), and ischemic stroke (Chen et al., 2013a). At the same time, Japanese researchers showed that increased consumption of red meat raised the risk of T2D only in men (Kurotani et al., 2013). In the study by a group of scientists from different countries (Rohrmann et al., 2013), it was shown that increasing the consumption of processed meat by 50 g/day increases not only cancer mortality but also the level of cardiovascular diseases (by 30%). Other studies showed that increasing the proportion of milk and nuts in the diet and reducing the amount of meat helps reduce the risk of high blood pressure (Weng et al., 2013). However, the association of unprocessed red meat with morbidity and mortality was not found by the group of Kappeler et al. (2013) in the multivariable-adjusted model (296,721 participants), although it showed a significant association with a high frequency of red and processed meat consumption in the model adjusted for age, sex, and race/ethnicity. However, this study used only a food frequency questionnaire and did not control for portion sizes. In contrast, another study demonstrated a 10–13% increase in the risk of stroke with increased consumption of red meat by 100 g per day or processed meat by 50 g/day (Chen et al., 2013a). As an alternative to beef consumption, Bison meat has been suggested to lower atherogenic risk (McDaniel et al., 2013). It has also been shown that regular consumption of horse meat may promote dietary intake of n-3 polyunsaturated fatty acids and may improve lipid profile and iron status in healthy individuals (Bò et al., 2013). At the same time, a large group of scientists showed that high overall meat consumption in Asian countries did not affect the risks of all-cause mortality, or cardiovascular disease and cancer mortality (Lee et al., 2013). Red meat consumption was inversely associated with cardiovascular disease mortality in men and women and cancer mortality in women. The authors also emphasised that the consumption of fish and seafood in Asian countries is much higher than in Western countries. It should be noted that according to the study, high consumption of red meat in Asian countries was up to 92.3 g/day (33.69 kg/year) for men and 50.9 g/day (18.58 g/year) for women. At the same time, average meat consumption in the United States was 122.8 kg/year in 2007. Therefore, high consumption of red meat in Asian countries is comparable to its low consumption in Western countries.

Overall, despite the somewhat contradictory results found by different researchers at first glance, there is a logical explanation for the differences. Notably, the negative effect of red meat consumption was not found in studies that did not consider the actual size of regularly consumed portions of meat. The inconsistency in outcomes of different research teams may also result from the heterogeneity of meat consumed. That's why Miller et al. (2013) underlined the importance of sample size and clear separation of meat consumed by the levels of heterocyclic amines, polycyclic aromatic hydrocarbons, nitrites, and nitrates. At the same time, a microbiota-mediated explanation for the atherogenic effect of meat was proposed by Koeth et al. in 2013 (Koeth et al., 2013). Studies by Koeth et al. show that the metabolism of abundant in meat L-carnitine by microbiota characteristic of the dietary status of omnivores leads to the formation of proatherogenic trimethylamine-N-oxide. The authors identified specific genera of microorganisms associated with plasma trimethylamine-N-oxide levels, but accurate

conclusions require identification of the species, strain differences, and microbial genes involved.

Since most studies link meat and fish consumption to changes in the risk of certain diseases, there is a need for an accurate assessment of consumption levels, which are usually defined through self-reporting. In this regard, there is a need to search for biomarkers of meat consumption to more accurately quantify the intake of meat products. To address this issue, Kuhnle et al. (2013) proposed using carbon and nitrogen isotopes to identify the short-term consumption of fish and meat. Altorf-van der Kuil et al. (2013) applied the other approach and revealed good results with urinary carnosine, 1-methylhistidine and 3-methylhistidine.

Another area of dietary research is examining consumers' consumption levels of red and other types of meat, assessing the impact of meat amount on diet quality and the environment. Thus, an assessment of the consumption of red and processed meat among Brazilians living in Sao Paulo showed that 81% of men and 58% of women exceeded the recommended amount, with a decrease in diet quality in men (de Carvalho et al., 2013). The authors recommended reducing meat consumption for a healthy and sustainable diet. At the same time, the importance of separating cohorts of confirmed vegetarians, pescetarians, and 1-day/week meat consumers was emphasised (Gilsing et al., 2013) to obtain more valid results. Based on an analysis of the British National Diet and Nutrition Survey 2000/2001, Aston et al. (2013) concluded that given the wide variation in meat consumption, reductions in overall consumption could be achieved by minimizing among consumers with high consumption levels.

On the other hand, reducing the amount of red meat, especially in infant diets, is of serious concern due to its association with iron deficiency (Moshe et al., 2013), and increasing its proportion in the diet of infants at 12 months of age contributes to an increase in haemoglobin and hematocrit levels (Olaya et al., 2013). However, meat contributed only 4.3% to iron intake among adults from five US ethnic groups, while vitamin B_{12} and zinc contributed 19.7% and 11.1%, respectively (Sharma et al., 2013).

Along with assessing consumer preferences regarding the cutting option and thickness of a piece of meat during cooking, there are works aimed at identifying readiness to reduce meat consumption in connection with animal welfare and the impact on the environment, as well as determining the contribution of reducing red meat consumption on agricultural production. Researchers have noted a low willingness to pay more for products that are good for animal welfare (Miranda-de la Lama et al., 2013) and the environment (Koistinen et al., 2013). Lehtonen and Irz (2013) concluded that a 20% reduction in red meat consumption is unlikely to reduce significantly livestock production, land use change, or greenhouse gas (GHG) emissions in Finnish agriculture.

Thus, the 2013 dose-dependent studies generally showed an association between higher consumption of red and processed meat and an increased risk of colorectal cancer, T2D, and stroke. However, such a link was not found for Eastern countries, which consume less red meat and more fish. A link was also noted between high red meat consumption and an increased risk of lymphoid cancer and acute myeloid leukemia. Reduction in meat-eating was recommended among consumers with high consumption levels. At the same time, the issue of the sufficiency of a meat-free diet, especially in children's nutrition, has not been fully resolved.

Health negative effects of meat: contemporary studies

In 2023, meat research in the direction of Nutrition and Dietetics is presented in several areas. Some part research is devoted to the quality, taste, and aspects of cooking meat products. These studies show that meat is an important nutrient in the human diet. At the same time, the largest share of investigation in the Nutrition Dietetics direction in 2023 is related to studies of the effects of meat consumption on public health and consumer attitudes toward a possible reduction in meat consumption (Slotnick et al., 2023; Wambogo et al., 2023).

The main contribution to global mortality is made by Non-communicable diseases, of which cardiovascular diseases and cancer occupy the first two places, and the 4th place belongs to diabetes (WHO, 2017). In 2023, a large proportion of research is devoted to the effect of excessive consumption of certain types of meat on some aspects of health. Noteworthy is the significant number of systematic reviews and meta-analyses, as well as results of long-term and large-scale observations and prospective studies, devoted to the comparison of diets and the effect of meat on the risks of both mortalities from various causes and the development of cancer, cardiovascular diseases, T2D, and other diseases.

Thus, according to Wu et al. (2023b), mortality and disability-adjusted life years attributable to high red meat consumption have increased steadily since 1999 worldwide (including 204 countries and territories). In turn, according to a meta-analysis by Wu et al. (2023c), red and processed meat are positively associated with the risk of mortality from all causes, cardiovascular diseases, and cancer, although this risk can be reduced to some extent through physical activity. According to Chung et al. (2023), fish consumption was associated with a lower mortality risk. However, Jensen et al. (2024) found a similar effect only among women. Kityo et al. (2023) also discovered that excessive consumption

of several meat types was linked to increased mortality from various causes in women, but not in men. In contrast, no gender dependence was observed for the increased consumption of processed red meat. In 2023, Yun and co-workers (Yun et al., 2023) confirmed the association between processed meat and the risk of colorectal cancer, while showing no correlation with other types of digestive tract cancer. A separate analysis by Ma and Qi (2023) using data from Our World in Data and Global Cancer Observatory found a significant positive correlation between red meat consumption and overall cancer incidence, particularly colorectal cancer. This correlation was consistent with a delayed effect, as a lag of 15–20 years between increased meat consumption and colorectal cancer incidence had been observed globally. A systematic review and meta-analysis of prospective cohort studies by Di et al. (2023), encompassing 3,780,590 individuals, found that high consumption of red and processed meats is associated with an increased risk of colorectal, colon, and rectal cancers.

However, conflicting findings emerged from studies on pancreatic cancer risk. Sun et al. (2023c) revealed no association between red and processed meat consumption and pancreatic cancer risk in a meta-analysis comparing the highest and lowest categories of 7,158 pancreatic cancer cases from 805,177 participants. In contrast, Kim Y.'s meta-analysis of 20 prospective cohort studies involving 3,934,909 participants and 11,315 pancreatic cancer cases (Kim, 2023) found a dose-dependent link between high meat consumption and pancreatic cancer risk, as well as an association with red and white meat intake.

In turn, the case–control study by Tayyem et al. (2023) discovered a significant correlation between daily meat consumption and stomach cancer risk. At the same time, Iranian researchers reported a link between chicken consumption and stomach cancer, which they attributed to the high prevalence of anemia in Iran (Narmcheshm et al., 2023).

The relationship between meat consumption and cancer risk in Eastern countries is a topic of interest, given the traditional association between increased meat consumption and Western diets. A systematic review and meta-analysis conducted by Cheung et al. (2023) found no link between red meat consumption and an increased risk of colorectal cancer for the highest versus lowest groups of red meat intake in Eastern European countries, including China, Japan, and South Korea. However, another study by Shimomura et al. (2023) discovered a correlation between processed meat consumption and the risk of acute myeloid leukemia or myelodysplastic syndrome in the Japanese population.

The significant increase in meat consumption in Asia over the past decade has raised concerns about its potential health impacts. A prospective cohort study of 113,568 adults in eight Korean regions found a positive association between high processed red meat consumption and all-cause mortality. A study by the Global Burden of Disease Collaborative Network analyzed data from 1990 to 2019 and found that some deaths and disability-adjusted life years attributed to diets high in red meat increased significantly over the years (Liu et al., 2023a). The analysis showed that the increased risk was not limited to colorectal cancer, but also included coronary heart disease and diabetes mellitus. Liu et al. (2023e) conducted the large-scale study examining the impact of long-term meat intake trends on the risk of T2D, based on data from the China Health and Nutrition Survey over 21 years. A team of researchers found a U-shaped relationship between meat consumption and the risk of T2D. According to the analysis, the risk of T2D was negatively correlated with meat consumption when it was less than 75 g/day, but when it exceeded 165 g/day the correlation became positive. Gu et al. (2023a) confirmed dietary recommendations to reduce red meat consumption to prevent T2D based on data from 216,695 participants. At the same time, an evaluation of randomised intervention trials and prospective cohort studies regarding white meat consumption did not reveal an association between cardiovascular disease and T2D (Ramel et al., 2023). Therefore, replacing red meat with white was considered justified.

The impact of increased processed meat consumption on diabetes risk in East Asian populations is similar to that in Western countries (Yu et al., 2023b). Moreover, similar to the results of Liu et al. (2023e), the U-shaped association between the consumption of unprocessed red meat and the risk of diabetes was identified by Yu et al. (2023b) in a dose–response meta-analysis of prospective cohort studies conducted in East Asian populations. The situation in developing countries regarding the impact of processed meat on chronic diseases has a trend similar to developed Western countries. Thus, although the mortality rate did not change in Brazil from 1990 to 2019, the age-standardised disability-adjusted life years indicator increased along with the increase in the cost of hospitalization and outpatient procedures for ischemic heart disease, colorectal cancer, and T2D attributable to the consumption of processed meat (Rocha et al., 2023).

Systematic review and meta-analysis of observational studies (43 studies with $N=4,462,810$ for cardiovascular disease and 27 studies with $N=1,760,774$ for diabetes) showed an association between consumption of both unprocessed and processed red meat with a higher risk of cardiovascular diseases, subtypes cardiovascular diseases

and diabetes regardless of gender (Shi et al., 2023). The connection was more pronounced in Western countries. Another study found that replacing just 100 g/week of red meat or 50 g/week of processed meat with fruits or cereals resulted in a small but statistically significant reduction in T2D risk, especially in men (Maukonen et al., 2023). Replacing red meat with various combinations of plant-based alternatives increased insulin sensitivity (Goode et al., 2024).

Dong et al. (2023) confirmed a positive association between increased red and processed meat consumption and incident coronary heart disease in a cohort study of 92,246 people using the UK Biobank. You et al. (2023), in turn, used United Nations data from 217 countries and conducted a correlation analysis between the consumption of total meat (red and white) and the incidence of cardiovascular diseases. They obtained evidence of a strong connection between meat consumption and cardiovascular diseases at the global and regional levels, including constant socioeconomic status, obesity, and urbanization. It is also noteworthy that this relationship was stronger in developing countries. A study of the 10-year risk of coronary heart disease among adult men in Korea found an increased risk associated with both overall high meat intake and high red meat intake (Jeong et al., 2023). A positive association between red meat consumption and coronary heart disease mortality overall and in men, but not in women, according to Fan et al. (2023) raises concerns about possible gender inequality. Using High-throughput targeted NMR spectrometry, plasma metabolites from the UK Biobank were studied and compounds associated with coronary heart disease and meat consumption were identified. The accumulation and deposition of triglycerides on arterial walls explain the increased risk of coronary heart disease with high consumption of unprocessed red meat and processed meat (Fan et al., 2023). The results of the 20-year ATTICA epidemiological cohort study (Damigou et al., 2023) led to an even more alarming conclusion: the risk of developing cardiovascular disease is influenced only by the type of meat consumed, but not by its frequency. The study showed an increased risk of cardiovascular diseases with the consumption of processed meat and an inverse relationship with the intake of white meat. In contrast to these results, there was no association between cardiovascular diseases outcomes and unprocessed meat, red and processed meat intakes among African American adults, except for a greater stroke risk associated with processed red meat (Bigornia et al., 2023). A study of the role of red meat in the development of cardiocerebrovascular diseases in China showed a decisive role of socioeconomic status in adverse cardiovascular diseases outcomes (Sun et al., 2023b). Increasing meat consumption by 50 g/day reduced the risk of mortality among rural and poor people, but increased the incidence of cardiovascular disease among urban and high-income people. In contrast, replacing red and processed meat with fish was beneficial for health and longevity (Chung et al., 2023).

It should be noted that revealing the connection between omnivores' intestinal microbiota and the atherogenic effect of meat consumption prompted Koeth with colleagues (Koeth et al., 2013) and other researchers to continue this investigation (Koeth et al., 2019). Nowadays, a representative of the intestinal microbiota of omnivores has been identified, which is responsible for the second stage of carnitine catabolism leading to the formation of trimethylamine-N-oxide. The species responsible for this transformation is *Emergencia timonensis* and associated microbial genes have been revealed (Koeth et al., 2019; Wang et al., 2019; Buffa et al., 2022). Thus, based on research data, the connection between meat consumption and the risk of cardiovascular disease seems to be proven nowadays.

Research has linked chronic metabolic acidosis to a high dietary intake of sulfur-containing amino acids from processed meats (Herter et al., 2023). Additionally, a study found higher odds of depression and anxiety in pregnant women who consumed high meat amounts, potentially due to increased serum uric acid levels (Alharbi et al., 2023). The impact of meat consumption on the microbiota is an area of ongoing research, but current data is limited and inconsistent (Almajed et al., 2023; Wang et al., 2023g).

A recent review of publications from 2022 and 2024 confirmed the identified risks associated with meat consumption. The findings suggest that meat consumption contributes to various health issues, including general obesity, central obesity, nonalcoholic fatty liver disease, and an increased risk of mortality in patients with inflammatory bowel disease (Chen et al., 2022; Khodayari et al., 2022; Kim et al., 2021).

A longitudinal study of frail individuals found that consumption of processed meat was associated with an increased risk of mortality from all causes and cardiovascular diseases, whereas the moderate consumption of unprocessed poultry and unprocessed red meat reduced the risk of mortality from all causes, cancer, and cardiovascular disease (Chen et al., 2024). Additionally, Nouri-Majd et al. (2022) discovered a possible association between meat consumption and the risk of prostate cancer.

The biochemical mechanisms underlying the potential negative correlations between increased consumption of various types of meat and the risk of chronic diseases are not yet fully understood. Several compounds,

including sodium nitrites and nitrates, heme iron and nitrosyl-heme, N-Nitroso compounds, heterocyclic amines, polycyclic aromatic hydrocarbons, 2-Amino-1-methyl-6-phenylimidazo[4,5-b]pyridine, and N-glycolylneuraminic acid, may be involved in these mechanisms (Cascella et al., 2018; Bellamri et al., 2023; Kotopoulou et al., 2023; Deveci & Tek, 2024). Recent research has also explored the role of plasmid-like DNA molecules in milk and meat in the early stages of tumour formation (Nikitina et al., 2024).

Studies have shown that N-glycolylneuraminic acid in red meat can induce intestinal disease by disrupting the intestinal barrier through transcriptional regulation of inflammatory factors (He et al., 2023a). However, other studies found no association between red meat consumption and inflammatory markers (Wood et al., 2023). Other research data have shown that excessive consumption of red and processed meat may lead to microbiota-mediated production of harmful metabolites (Mervant et al., 2023).

The recent umbrella review by Zhang et al. (2023c), based on data from 40 meta-analyses, concluded that "red and processed meat consumption seems to be more harmful than beneficial to human health". Conversely, scientists from the Institute for Health Metrics and Evaluation argue that the current evidence on the harm of unprocessed red meat is insufficient to make conclusive recommendations and advocate for more rigorous and powerful studies to investigate the link between unprocessed red meat and chronic diseases (Lescinsky et al., 2022).

Seafood consumption is generally associated with a variety of health benefits, in particular a reduced risk of cardiovascular mortality due to the presence of ω−3 polyunsaturated fatty acids. However, there is evidence of an increase in the level of uremic toxin trimethylamine N-oxide produced by the gut microbiota when consuming a diet rich in deep-sea fish (Mafra et al., 2023). Other negative effects of seafood include an increased risk of poisoning associated with the accumulation of biotoxins, heavy metals and microplastics (Santonicola et al., 2023; Tacon et al., 2024). At the same time, a detailed study of the scientific literature on the topic allowed Tacon et al. (2024) to conclude that the nutritional value and health benefits of eating fish and seafood significantly outweigh the potential risks.

The scale of current research on the impact of excessive meat consumption on consumer health is noteworthy. Many studies involve even millions of consumers and hundreds of countries. The effect of high consumption of red and processed meat on an increased risk of cancer in general, in particular colorectal cancer, has been fully demonstrated in recent years. Discrepancies in the results of individual studies, especially those concerning other types of cancer, are usually associated with study design, population, or dietary assessment methods. Thus, comparing the consumption of large and small meat doses without assessing the dose-dependent relationship of meat consumption with health usually leads to negative results. The reasons lie primarily in the significant differences in the levels of meat consumption in different countries and among different categories of consumers. For example, high levels of red meat consumption for the Asian population are comparable to low levels for Western countries.

Growing concern about meat

Based on scientific research on the increased risk of non-communicable diseases, health authorities are increasingly recommending moderate meat consumption, especially red and processed meats. In 2015, the International Agency for Research on Cancer classified red meat consumption as “probably carcinogenic to humans” (Group 2A) and processed meat consumption as “carcinogenic to humans” (Group 1). The impact of excessive meat consumption on increasing the risk of mortality from all causes, cancer, cardiovascular disease, and T2D, along with the presence of pathogens and parasites, are growing concerns about meat.

Research into the health of meat is not the only cause for concern and awareness of the need to reduce consumption. Global meat production is growing steadily and reached 371 million tons of slaughter equivalent in 2023 (FAO, 2024), led in 2022 by China (101,870 million tons), the USA (43,395 million tons), the European Union (37,165 million tons) and Brazil (22 296 tons) (Our World in Data, 2024). Global meat demand is forecasted to rise steadily (OECD-FAO, 2021). According to Our World in Data (2024), the average per capita meat supply reached 117.4 g in 2021. In most countries, this figure is 165 g, and in some countries is more than 300 g of meat per day with a record for Hong Kong of 402.37 g. At the same time, this index ranges from 40 to 165 g or less than 40 g of meat per day in most African countries. The same applies to southern and south-western Asia, Oceania and North Korea. The average total meat supply in the Americas in 2021 was 257.51 g per day per capita, and the Asian average was 91.51 g, with variations between Asian countries.

At the same time, quantitative statistical data based on the production and import of meat in carcass weight equivalent do not fully correspond to the actual meat consumption due to meat losses at various stages, including retail and consumption (Karwowska et al., 2021). Research by the National Cattlemen’s Beef Association (Lau et al., 2023), based on the Nutrition Examination

Survey of 2001–2018, suggests daily consumption of 42.2 g of total beef per capita by Americans aged 2 years and older. This intake is within the daily serving of 104.9 g (28 oz/week) of meat, poultry and eggs recommended by the Dietary Guidelines for Americans, 2020–2025 (DGA, 2020), for a diet within 2000 cal. However, Lau et al.'s study does not take into account other types of meat, so it cannot fully characterize overall meat consumption. A cross-sectional study conducted in New York City in 2014 found quite high levels of meat consumption, exceeding DGA recommendations and showed the dependence of meat consumption on ethnic differences (Choi & Lee, 2023). Thus, according to surveys, among young American women, African Americans consumed more meat (64.2 kg/year = 175.9 g/day), followed by immigrants from the United States. East Asians (53.6 kg/year = 146.8 g/day), whites (46.9 kg/year = 128.5 g/day) and Hispanics (35.8 kg/year = 98.1 g/day). It is also known that there are gender differences in the amount of meat consumed (Predanócyová et al., 2023). Accurately estimating meat loss and waste is also a significant challenge, both at each stage of the food chain and as a whole (Colombani & Brunner, 2024). The existing gap between production/import and actual consumption of meat indicates the amount of waste produced by the industry, which, while not affecting health, nevertheless makes a significant contribution to the aggravation of the environmental problem (Karwowska et al., 2021) and weakens the economy.

Recycling waste from production can reduce the environmental impact. Thus, using poultry manure to produce biogas helps avoid methane and ammonia emissions, which reduces the indicators of climate change in the Brazilian chicken meat cycle by more than 50% (Dos Santos et al., 2023). Another possible area for reducing GHG emissions in the meat supply chain is the transportation stage. Thus, research by Zhang et al. showed a 24.19% reduction in emissions from lamb production due to better planning (Zhang et al., 2024b). However, it is emphasised that the bulk of emissions directly related to production are unlikely to be reduced. An attempt at a compromise between sustainable meat production and climate change mitigation is the combination of high-yield pastures rich in legumes, maximizing grass consumption, reducing herd size and increasing animal productivity, resulting in the smallest reduction in meat production (28%) and the largest (30%) cut in GHG emissions (Pinsard et al., 2023).

Meat production can impact the environment by using resources and energy and generating waste. La Barbera et al. (2023) emphasize that intensive livestock farming not only uses 1/3 of arable land and produces ammonia emissions from manure, but also leads to the depletion of freshwater reserves, disruption of ecosystems, and loss of biodiversity. Calculations have shown that a 1% increase in meat consumption will raise GHG emissions by 0.91% (Raihan, 2023). Global GHG emissions increased by 1.7 per cent in 2022 (Tiseo, 2023). The main contribution to GHG emissions leading to climate warming comes from carbon dioxide (75.24% as of 2020) mostly from fossil fuels and methane (19.47%) (Ritchie et al., 2020) mostly from livestock. Manure and gastroenteric methane releases from livestock account for 32 per cent of human-caused methane emissions (McArthur, 2021).

Methane is comparatively short-lived. Even though CO_2 is the most abundant GHG, methane has 28 times higher global warming potential and a much greater role in warming the planet (Statista, 2023; Ritchie & Roser, 2024; Bridger Photonics, 2024). If we take into account data for 20 years, it is 80 times more potent at warming than carbon dioxide (McArthur, 2021) because its breakdown is connected with CO_2, water vapour, ozon, and some molecules that act as a "detergent," cleaning methane and many other pollutants from the air. CO_2 remains in the atmosphere for hundreds to thousands of years and even if its emission ceases, the effect could only be provided after 100 years. Methane lifetime is 10 years, so, its reduction can give tangible results in the coming years and keep humanity from a critical rise in temperature of 1.5 °C. Methane can cause a large spark in warming, as well as a sharp decline in it emissions can quickly limit the amount of atmospheric warming (Gibbens, 2024).

In 2022, methane emissions increased compared to 2020 from 10.13 billion t to 10.49 billion t (Ritchie et al., 2020), reaching 21% of total GHG emissions. Production growth of poultry, pigmeat, beef, and sheepmeat consumption is projected to grow 15%, 11%, 10%, and 15%, respectively, by 2032 (OECD-FAO, 2023). Poultry is considered to have the least carbon footprint among other types of meat and is expected to account for 41% of the protein consumed from all meat sources in 2032. Assessing the impact of chicken meat production "from cradle-to-grave" on global warming, acidification, and eutrophication in Indonesia showed that eating 1 kg of fried chicken costs a global warming impact of 5.86 kg CO_2eq, acidification of 38.3 g SO_2 eq, and eutrophication of 24.1 g PO_4^{3-}eq (Azmi et al., 2023). At the same time, according to global statistics, the footprint of beef (average), excluding methane, is 36 kg of CO_2 eq per kilogram, which is four times larger than global emissions from chicken and 10–100 times larger than GHG emissions from plant-based foods (Ritchie & Roser, 2024). When methane emissions are included, this figure is almost double, and for non-dairy beef herds, the global mean emissions for one kilogram is 100 kg of CO_2eq. Calculated per kg of protein, the climate impact of plant-based

meat analogues (PBMA) is from 4 to 12 kg CO_2 eq (Shanmugam et al., 2023) while the protein content of PBMA is 14.1–19.8% (Yang et al., 2023d).

The list of possible consequences of global warming includes increased average temperatures, storms, droughts, wildfires, expanding deserts, rising sea levels, extinction of species and their replacement by invasive pests, food shortages, increased health risks, increased risk factors causing poverty and forced displacement of people (United Nations, 2024). The rise in global temperature (above the 1850–1900 average) of 1.5 degrees and above leads to long-term and irreversible changes and death of some ecosystems (United Nations, 2018). The current level of global warming is 1.15 °C and global temperatures continue to rise. According to the World Meteorological Organization (2023), "there is a 66% likelihood that the annual average near-surface global temperature between 2023 and 2027 will be more than 1.5 °C above pre-industrial levels for at least one year. There is a 98% likelihood that at least one of the next five years, and the five-year period as a whole, will be the warmest on record." To reduce the adverse impacts of climate change and associated loss and damage, the Paris Agreement set long-term goals to limit the global temperature increase in this century to 2 °C and limit it further to 1.5 °C.

Another reason for concern about the mass consumption of meat and the increase in its production is the aspect of animal welfare, which includes, first of all, ideas about the inhumanity and abnormality of killing animals for food and the suffering of animals in the process of growing and slaughtering for food. Followers of veganism (complete rejection of animal food) make up only a small segment of the world's population. Thus, in 10 countries of the world the percentage of vegans ranges from 3 to 9%. In another 10 countries, between 2% and 4.1% of the population eats only plant foods. In other countries, vegans make up an even smaller proportion of the population or data are missing (Veganism by Country, 2024). There are significantly more vegetarians. In 16 countries of the world, the percentage of vegetarians is 10% or more (Vegetarianism by Country, 2024). Other people are omnivorous meat eaters. Many people would like to eat less animal food due to concerns about animal welfare, health and environmental impacts, but are too attached to meat (Roozen & Raedts, 2023). Most people justify and defend their eating meat with the help of "4Ns" arguments: eating meat is normal, necessary, nice, and natural (Mroz et al., 2024; Roozen & Raedts, 2023). People consider eating animal flesh normal and natural because they are omnivores and they like the taste of meat. Eating meat is considered physiologically necessary and replacing some components with plant foods is regarded as impossible. It is also noted that meat consumption is supported by positive emotions from eating. Hiding of animal origin in main digital sources of dietary information allows normalizing the "meat paradox" and legitimizes eating meat (Mroz et al., 2024).

At the same time, another part of the research deals with the issue of animal welfare in a slightly different way. Several works aim to study the influence of stress experienced by meat animals during production (including during slaughter) on meat quality. The stress experienced by animals under various circumstances raises concerns about the possible reduction in the quality of meat produced (Faucitano & Nannoni, 2023). Some studies suggest the effects of stress on tissue oxidative stress indices, carcass characteristics and meat quality (Mohapatra et al., 2023; Riggs et al., 2023; Wang et al., 2023b). It also emphasises the impossibility of eliminating animal stress at the pre-slaughter stage (Palka et al., 2023). Dietary tryptophan supplementation has been suggested to improve meat quality in nervous Hu sheep, reducing the stress response (Wang et al., 2023c). At the same time, some publications indicate that the manifestation of humanity to animals used for food is not officially accepted and is considered inappropriate or inconvenient. Thus, described by Njoga et al. (2023) horrible treatment of animals in the pre-slaughter period is not uncommon. At the same time, most researchers and consumers are more concerned about the effects of stress on meat quality than about animal suffering. Some publications concerning the method of slaughtering animals are addressed to halal standards for meat production. An important factor for many religious meat consumers is the lack of stunning of animals before slaughter. In this regard, religious meat consumers are more concerned with compliance with halal production requirements than with animal welfare issues (Govindaiah et al., 2023).

An analysis of the number of articles published since 2013 indicates the growth of interest in meat topics in recent years. The total number of scientific publications from the Web of Science database on all topics increased from 2018 to 2023 by 1.27 times. The ratio of the number of publications in the field of meat published in 2023 to similar publications in 2018 was 1.44 for articles with the word "meat" in the title, and 1.50 for publications with the word "meat" in the abstract and title, which is comparable to the growth number of publications with the words "food", "fruit", "bread", and "beverage" in the title (Fig. 7).

At the same time, the number of publications on such food products and nutrients as corn, milk, potato, vegetable, wheat, protein, and vitamins did not increase over the specified period. The number of publications with the terms "climate change", "global warming", or "animal welfare" in the title or topic increased even more

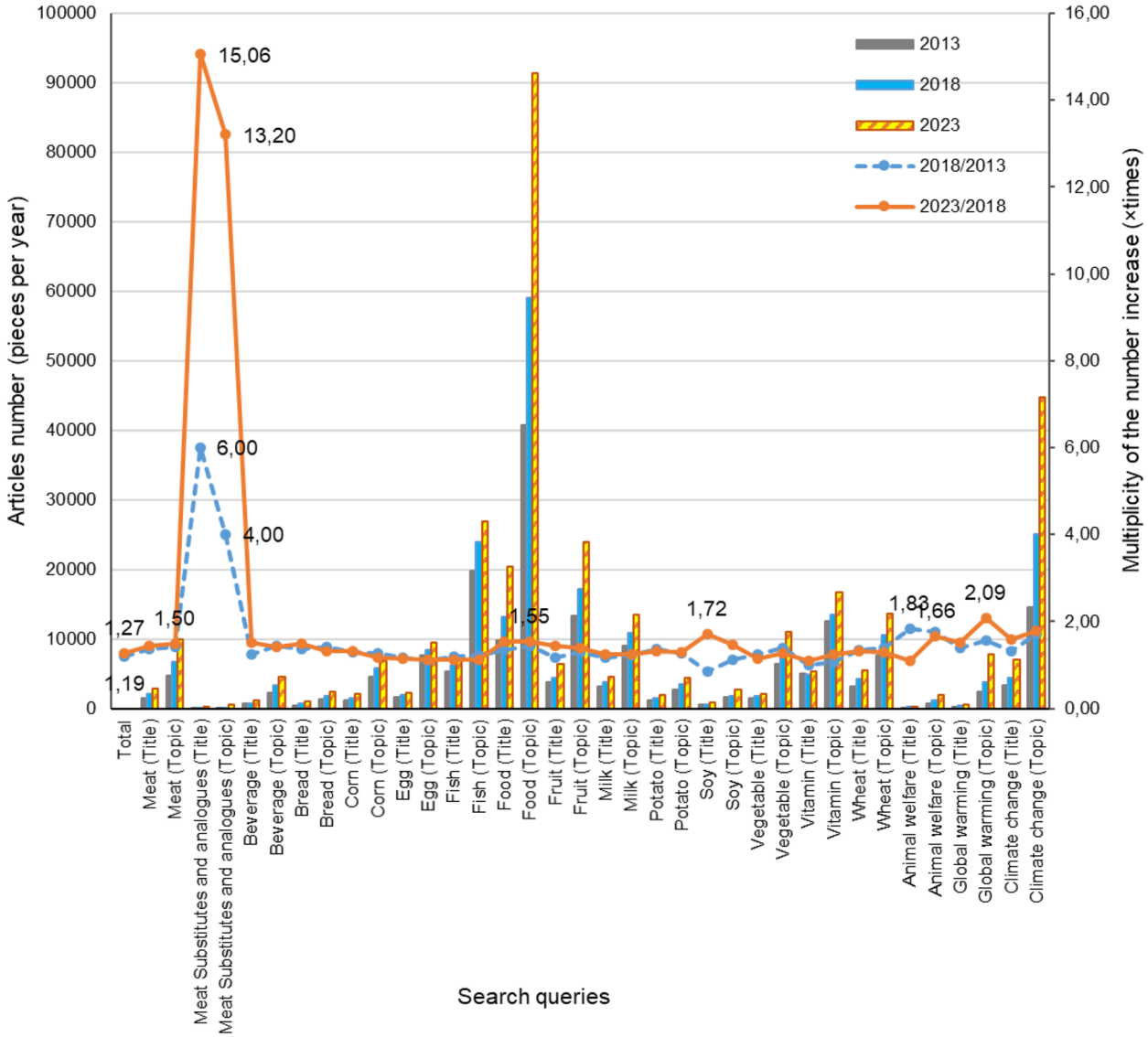


Fig. 7 Change in the number of scientific publications on nutrients and global topics from 2013 to 2023

(1.56–2.09 times) both from 2013 to 2018 and from 2018 to 2023, and articles with the word "soy" in the title have increased by 1.72 times over the past 5 years. The number of publications that include in the title or topic any of the definitions of meat substitutes (plant-based meat, meat-analog, meat substitute, meat alternative, alternative meat, cell-based meat, cultured meat, cultivated meat, 3D-printed meat, lab meat, lab-grown meat, or mock meat increased from 2013 to 2018 by 4–6 times, and from 2018 to 2023 by 13.20–15.06 times. It is obvious that there is a surge in the number of publications related to meat substitutes and analogues stems from such global problems of our time as the environmental problem of global warming and the food problem of providing the planet's population with the necessary amount of food and is aimed at finding possible ways out of the current situation.

Meat alternatives

The number of publications regarding various meat substitutes and alternatives has increased dramatically. Four clusters of terms from publications on meat analogues and substitutes were revealed (Fig. 8). These clusters are product properties, consumer acceptance, cultured meat, and product composition. Cluster product properties also include the technology of receiving the products. The Consumer Acceptance and Cultured Meat clusters are most closely related since consumer perception of

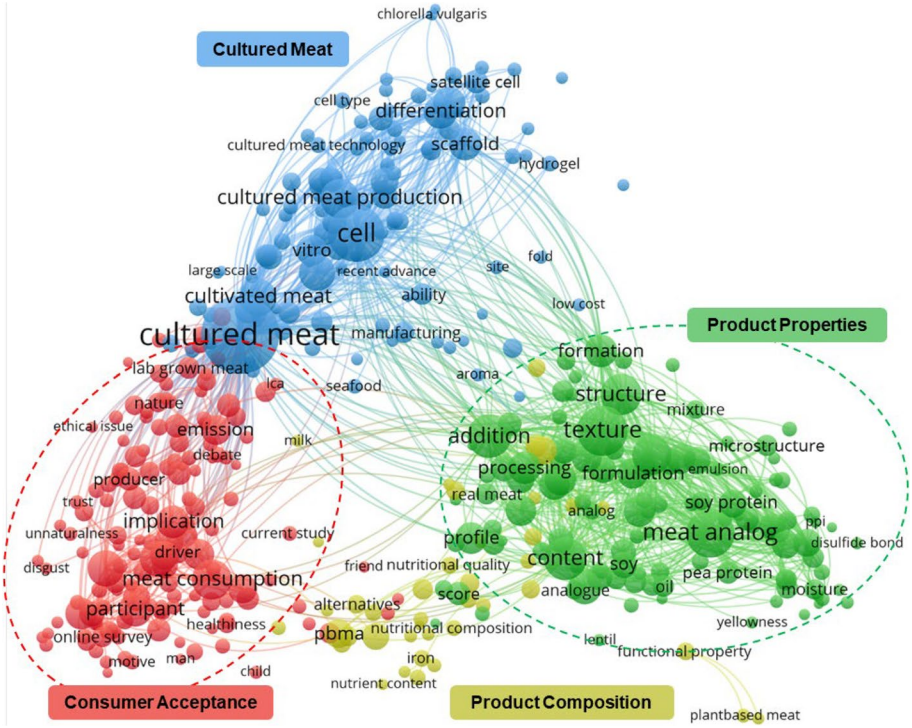


Fig. 8 Mapping of repeated terms in publications on meat analogues and substitutes (OpenAlex)

laboratory meat is the main factor influencing its further promotion. The nutritional composition of analogue products (product composition) follows from the properties and main components of the product and is also related to consumer perception.

A significant part (14.85% in 2023 and 16.99% in 2024) of publications with the word "meat" in the title in the Web of Science database relate to meat alternatives. The number of publications on meat alternatives increased by 3% in the first half of 2024 compared to half of the publications in 2023. At the same time, the number of publications with "meat" in the title but not relating to meat alternatives decreased by 12.4% in this period.

Both plant proteins (cereal, pulses, oil seeds, seaweed) and non-vegetable proteins (mycoprotein, insect, myofibril) are currently considered as the available meat alternatives (Arunachalam et al., 2023; Rojas-Tavara & Jesus Donayre-Torres, 2023; Vallikkadan et al., 2023). The main source of plant protein is soy, however plant-based meat alternatives can also use proteins from peas, chickpeas, lentils, rice, wheat, oats, lupin, fava beans, rapeseeds, and hemp (Andreani et al., 2023; Costa-Catala et al., 2023; Munialo & Vriesekoop, 2023; Yu et al., 2023c). A mixture of legumes and cereals is well justified because deficiencies of sulfur amino acids and lysine are complemented in a whole product (Costa-Catala et al., 2023). The need to add fat and create meat-like texture and colour also requires the inclusion of oils, binning agents, colourants, and flavourings, which can originate from vegetables, berries, plant resins, and others (Andreani et al., 2023; Costa-Catala et al., 2023). A third of all research on meat analogues involves cultured meat. *Tenebrio molitor* larvae are the most studied source of insect-derived alternative protein. Other insect options are being considered promising alternatives, but the issues of biosafety and allergies have not yet been resolved (Kang et al., 2023; Ruskova et al., 2023). The most promising candidate for mycoprotein production is *F. venenatum* A3/5, which has high protein purity, fibrous texture, and low toxicity (Khan et al., 2024).

The development of structuring methods for the closest reproduction of the texture, i.e., matrix and fibre, of meat is the main direction of work in the field of meat substitutes (Seo et al., 2023; Vallikkadan et al., 2023Van der Sman & van der Goot, 2023). Advanced technologies, such as shear cells and electrospinning, are used along with extrusion to reproduce fibres in plant-based meats (Arunachalam et al., 2023; Lee et al., 2023). Mimicking the sensory profile of meat is the most difficult part when developing plant-based substitutes (Kumari et al., 2023). In turn, stem cell technology, microcarriers, and scaffolds are used to form aligned tissues of cultured meat (Lee & Choi, 2024).

The assembly methods in culture meat production are 3D bioprinting, cell layering, and spinning (Santos et al., 2023). Various cells, such as adipocytes, chondrocytes, fibroblasts, and endothelial cells, are used to impart textural and sensory properties to lab-meat products (Kumar et al., 2023b). A separate problem is the co-culture of fat and muscle cells, which leads to suppression of myogenesis in favour of adipogenic differentiation (Pallaoro et al., 2023).

The regulatory framework for cultured meat has not yet been fully developed and may differ in different regions. There is also no universal approach to cultured meat testing and safety assessment (Gu et al., 2023b).

The possibility of reducing meat consumption is associated not only with its complete replacement with certain alternative products. Hybrid products are also considered a suitable option to facilitate the transition to healthier and more sustainable diets (Ryder et al., 2023). So-called hybrid meats are a new class of products in which part of the meat product is replaced by alternative protein sources, for example, of plant origin. However, the share of alternative proteins in such products usually does not exceed 20–30% due to negative consumer assessment (Baune et al., 2023; Bermúdez et al., 2023; Zhang et al., 2024a). The attitude towards reducing meat in the diet is also a separate issue, which has been the subject of many studies.

Consumer preferences and meat reduction

Much of the research in recent years has assessed the willingness to limit meat consumption among omnivores due to impacts on the environment, health, and animal welfare (Turnes et al., 2023). It is noted that, regardless of the accumulating evidence about the negative health and environmental impacts of meat, most people may be reluctant to reduce their meat consumption, and meat options may be more attractive to consumers than meat-free options (Pechey et al., 2021; Siegrist & Hartmann, 2023; Valli et al., 2022). For example, De Valck et al. (2023) studies show that only 21% of consumers attach great importance to carbon dioxide emissions. Bimbo (2023), in turn, demonstrated the importance of climate change awareness in reducing red meat. At the same time, Aureli et al. (2023) underlined the insufficient awareness of respondents (45%) regarding the impact of meat consumption on the environment. Research by Grummon et al. (2023) concluded that the messages about the health and environmental impacts of red meat consumption could reduce meat selection in certain types of restaurants. Findings from other studies suggest that environmental and animal welfare concerns do not significantly influence intention and willingness to reduce meat consumption (Seffen & Dohle, 2023). Simultaneously, the health effects of meat were more effective in the intention to reduce consumption. However, the reduction of meat in the diet caused respondents to feel a lack of meat.

An attachment to meat is often cited as a major factor in resisting changes (Kershaw et al., 2023). Meat seems too attractive to be replaced by plant proteins, cultured meat, or insects (Siegrist & Hartmann, 2023). Thus, "meat fans" (76% of surveyed consumers) have a greater number of positive attitudes related to meat consumption, compared to "meat reducers", while the attitude towards the content of healthy nutrients in meat was the same in both groups (Melios & Grasso, 2024). Liking conventional meat is also the main reason (58%) for reluctance to try cultured meat (Choudhary et al., 2023). Factor analysis determined that the latent factor explaining more than 50% of depression from protein source substitution was the importance of meat. According to other data (Aureli et al., 2023), 25.6% of respondents consider meat a very important and indispensable product.

The first question most people ask when choosing plant-based meat alternatives is whether they are sufficient for a healthy diet and the bioavailability of the nutrients they contain. Interestingly, studies by Zandstra et al. (2023) showed no difference in the satiating power of animal meat dishes and plant-based meat dishes when consumed as part of a full meal at home. It was concluded that dishes made from plant-based meats can be just as filling as dishes made from animal meats. Other researchers have studied the adequacy of individual nutrients in meat-based and plant-based diets, with generally similar results. Thus, a study of the nutritional intake of children and adolescents on a plant-based or meat-based diet showed that in all groups, there are risks of malnutrition (Neufingerl & Eilander, 2023). Children on a plant-based diet are at risk for inadequate intakes of vitamin B_{12}, iron, and zinc, and children on a meat-based diet have insufficient intakes of fibre, saturated and unsaturated fatty acids, and are at risk for insufficient intakes of folic acid and vitamin E. In turn, Latunde-Dada et al. (2023) determined the bioavailability of minerals in beef and plant-based hamburgers. Beef burgers contained more iron, but the bioavailability was comparable to that of plant-based burgers. At the same time, beef burgers were superior to plant-based burgers in terms of zinc content and bioavailability. Zinc bioavailability was comparable to that of meat only in the mycoprotein hamburger. However, plant-based meat substitutes were excellent sources of calcium, copper, magnesium and manganese. The researchers concluded that plant-based burgers can provide adequate amounts of iron and zinc as part of a varied diet. In a study by Kebebe et al. (2023), who compared the diets of meat-eating

and non-meat-eating people regarding recommended intakes of certain nutrients, also showed that people who did not consume red meat were at increased risk of calcium, vitamin D, energy and potassium deficiencies, while consumers of red meat were at increased risk of deficiencies in dietary fibre, vitamin A and magnesium. In addition, fibre and calcium intakes and daily caloric intake were below recommended values in both groups. In theoretical calculations for a conservative transition to a diet with the replacement of various amounts of meat and milk with plant analogues, the consumed amount of iron, on the contrary, increased by 15% (Lawrence et al., 2023). However, vitamin B_{12} and iodine intakes were reduced by 19% and 14% respectively. Consumption of zinc, phosphorus, riboflavin, niacin and n-3 long-chain fatty acids (decreased by 6–8%) was less affected. In the accelerated meat reduction scenario, long-chain n-3 fatty acids, vitamin B_{12}, and niacin were reduced by 6% to 7%, and iron and sodium intakes were increased by 12% and 6%. Unfortunately, not all studies compare changes in individual intakes with recommended daily allowances. However, the results show that if specific micronutrients and vitamins are not adequately consumed, existing nutritional deficiencies may be significantly exacerbated. However, a 6-week clinical study by Itkonen et al. found no differences in vitamin D and calcium intake or markers of mineral metabolism when replacing red and processed meats with soy-free legumes (Itkonen et al., 2024). Additionally, reducing protein intake while reducing meat and dairy intake (Habumugisha et al., 2024) did not show differences in body weight, body mass index, waist circumference, body fat, or lean body mass. To more fully evaluate plant-based meat substitutes in comparison with meat products, further analysis of the total composition and bioavailability of macro- and microelements is required, as well as an assessment of the role of these products in the overall diet, including frequency of consumption and dietary diversity.

A literature review shows that nutrient deficiencies are possible in both plant-based and meat-based diets. The key problems with an insufficiently developed plant-based diet are deficiencies of protein, essential fatty acids, vitamin B_{12}, iron, calcium, zinc, and vitamin D. The main deficiencies of a meat-based diet are: dietary fibre, vitamin A, and magnesium. According to a review of the medical literature by Plotnikoff et al. (2023), a well-designed plant-based diet can be both sufficient and beneficial with sufficient vitamin D intake from the sun or supplements. Nutrient absorption can be increased by soaking, sprouting, and fermenting, and the interactions of various nutrients with each other can also be taken into account, which is often not considered when formulating diets.

Focusing on maximum similarity to the meat product and reproducing the texture of meat (Liu et al., 2023c; Wang et al., 2023h) is also a source of problems in the willingness to accept alternative products. The impossibility of completely reproducing meat quality and sensory characteristics in substitutes cannot be denied. The category of meat substitutes includes products intended to replace meat, but at the same time, according to Hoogstraaten et al. (2023) implicitly appeal to a vegetarian/vegan diet. The names of plant-derived analogues related to the corresponding traditional meat products may mislead consumers who expect products with similar quality characteristics (Daszkiewicz et al., 2023). The intrinsic properties of meat are more important to most consumers (De Valck et al., 2023). Moreover, ultraprocessing and ultraformulation to obtain fibres from proteins of other origins compromise nutritional value and safety (Xiong, 2023). Thus, technological solutions alone are not enough to significantly reduce meat consumption (Siegrist & Hartmann, 2023), and additional measures are needed.

Research shows that legumes, eggs and fish are the most preferred sources of protein to replace meat (84–77%), while insects and insect-based products are less preferred (67%) (Aureli et al., 2023). Only 6% of respondents among meat scientists agreed to regularly buy cultured meat, pay more for it, and replace regular portions of meat with it (Choudhary et al., 2023). Perception of insects and cultured meat as meat substitutes is low (Siegrist & Hartmann, 2023). New highly processed meat analogues (such as Quorn and the Impossible Burger) have higher perceptions (Siegrist & Hartmann, 2023) and can replace meat without changing its format but are often perceived as less tasty than meat and have a negative impact on health. Only plant-based proteins were characterised with high acceptance.

Reynolds et al. (2023) modelled five substitution scenarios for red and processed meats, taking into account health, equity, GHG emissions, and costs. In their work, the researchers used an established life table model and data from New Zealand. Meat replacement with minimally processed plant-based foods was consistently more effective than the other scenarios across all outcomes.

Consumer surveys have found that perceived taste is most important when evaluating a meat substitute, but perceived naturalness and familiarity are also important (Fidder & Graça, 2023). In this regard, the willingness to purchase hybrid and cultured meat products is lower than the willingness to buy plant-based meat substitutes (van Dijk et al., 2023).

The purchasing intention is influenced by composition information, sociodemographic characteristics, and behavioural attitudes toward beef, mixed foods, and

plant-based foods (Li et al., 2023a). The acceptance of meat alternatives largely depends on the availability of information about the health effects of excessive meat consumption. Thus, Italians consuming red/processed meat in quantities exceeding those recommended by the World Health Organization expressed their intention to reduce their meat consumption after receiving information on social (data on the number of deaths associated with a meat-rich diet) and individual (percentage increase in cancer risk with a specific increase in the dose of meat, information about the risk of other chronic diseases) consequences of excessive meat consumption. Women, respondents with children, and those with a low health status perception (Caso et al., 2023) were most susceptible to the effects. However, it found that the higher price of meat alternatives could be a barrier to reducing meat consumption for the poorest in society (Coffey et al., 2023).

Meat consumption is not uniform and depends on many factors, including income level, gender, ethnic differences, beliefs, and others. Prescriptive and personal norms, and sociopolitical ideologies, exert strong influences in favour of meat consumption (Choma et al., 2024; Wolfswinkel et al., 2024). Differences between dietary groups in attitudes and moral concern for animals were explored to understand the psychological underpinnings of animal product consumption. The results showed a relationship between a positive attitude towards animals and the strength of moral emotions, on the one hand, and reduced meat consumption. However, women held fewer justifying beliefs than men in groups that consumed animal products (Ioannidou et al., 2023). In general, older women and those with higher levels of education were more likely to reduce their meat consumption (Carvalho et al., 2023). On the issue of the established connection between meat consumption and masculinity, it was found that men who support the use of physical violence and attach great importance to sex eat more meat (Camilleri et al., 2024). Men experiencing masculinity stress are more likely to choose PBMA, provided they are presented in the context of a masculine product (Leary et al., 2023).

Knowledge about substitutes, income level, and the presence of children are positively associated with willingness to pay, while age is negatively associated (Chen et al., 2023a; Leung et al., 2023). In general, educated, older and rich people consume all meat types less frequently. It has been shown that vegetarian status is associated in statistical analysis with highly educated people over 45 years of age, mostly living alone and having low self-rated health. However, study results (Ponzio et al., 2023) suggest that the long-term health of vegetarians is good or better than that of comparable non-vegetarians in terms of obesity and coronary heart disease.

Many researchers focus on the psychology of meat consumption, decision-making processes and behaviour change towards reducing meat consumption (Carfora & Catellani, 2022; Ostermann et al., 2024; Reuzé et al., 2023; Strässner & Hartmann, 2023). Associations of particular ethical concern, weight control, sensory attractiveness and mood, have been shown to vary by gender, age, marital status or body mass index (Hentilä et al., 2023). Individual warning labels are effective (Grummon et al., 2023; Hughes et al., 2023). Choices can also be influenced by influencers (Leite et al., 2024; van der Horst et al., 2023), public image (Castellini et al., 2023) and political views (Kershaw et al., 2023; Yule & Cummings, 2023).

At the same time, a significant barrier to reducing meat consumption is Deliberate ignorance of information (Kadel et al., 2023). At the same time, clear gaps were identified between stated and actual behaviour concerning meat reduction (Schäufele-Elbers & Janssen, 2023). Thus, the decision-making process regarding meat consumption is complex and dependent on many factors (Fig. 9).

It can be concluded from recent studies that meat replacement strategies should target different populations, namely focusing on multiple dietary motivations in various subgroups (Hentilä et al., 2023). At the same time, efforts to reduce processed meat consumption should target consumers with high consumption levels (Jensen et al., 2024). But it also notes that despite the wide range of substitutes on offer, meat eaters remain sceptical about their taste, and substitutes are more likely to resonate with non-meat eaters than meat eaters (Van de Wouw et al., 2017; Hansen & Wethal, 2023; van Dijk et al., 2023).

Focuses and perspectives Meat has been a staple food for centuries for many peoples of the world. An analysis of research over the past decade has shown that the bulk of meat research is still published in three main areas of the Web of Science: Food Science Technology, Agricultural Dairy Animal Science, and Veterinary Sciences. Meat quality research forms the basis of all meat research. The bulk of publications in the field of meat quality are published in Agriculture Dairy Animal Science direction and are devoted primarily to studying the influence of various dietary supplements in the diet of meat animals on meat quality. The research shows a positive effect of all supplements studied most likely due to an expanded more balanced diet and a more regular intake of various micronutrients into the animal's body. Other features of keeping and slaughtering animals also remain in the field of view of specialists. The aspect related to the compliance

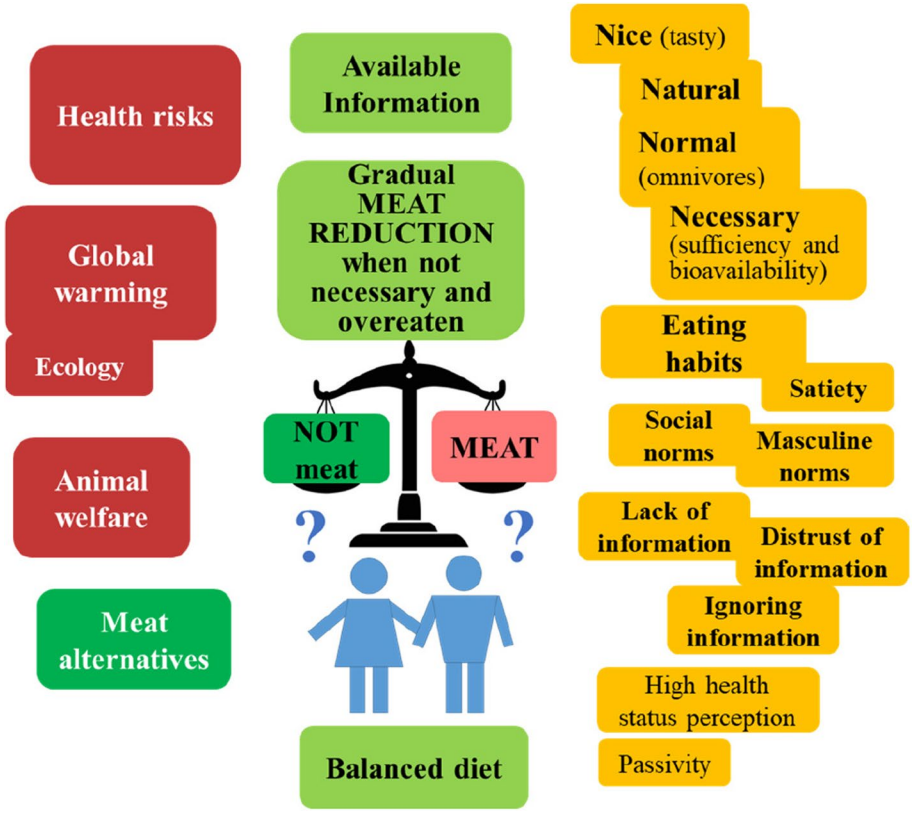


Fig. 9 Weighing the pros and cons of meat question and rational solution

of spiritual quality with the slaughter method and the resulting meat product has expanded. However, religious beliefs sometimes come into dissonance with the issues of animal welfare. There is also interest in the interrelation of slaughter methods that help alleviate animal suffering and the quality of the resulting product.

Significant progress in meat quality, safety, and preservation in recent years is associated with the development of new research methods. A big leap has been made in the field of meat authentication, which is primarily associated with the need to detect adulterations. Changes in this area have occurred not only due to the widespread use of multiplex-PCR but also to the development of such new molecular methods as droplet digital PCR and isothermal polymerase spiral reaction. Further expansion of research in this direction is also expected. In the field of meat preservation, it is worth noting the development of methods for detecting various chemical compounds that make up meat and are markers of quality or spoilage. The development of electronic nose, eye, and tongue helps to obtain fast and high-quality results. Great progress is made in the meat preservation sector, which helps reduce meat losses and contributes to solving environmental problems. In this area, solutions using special indicator films that demonstrate the shelf life of products are interesting.

However, a general look at meat research revealed several significant changes in research from 2013 to 2023. The summary share of publications in the three main Web of Science areas publishing meat research has fallen over the past decade from 89 to 73%. The most pronounced decrease in the share of publications in the field of meat was noted in the areas of Food Science Technology (from 45.35% to 38.06%), Applied Microbiology and Biotechnology (from 6.56% to 2.80%), Microbiology, and Agriculture Multidisciplinary. The decrease in the share of publications in the field of meat microbiology is most likely due to sufficient knowledge of its microbiota and a small number of published results attempting to control meat pathogens using starter and protector cultures. The share of publications in Oncology and Toxicology also decreased from 2013 to 2023, but, on the contrary, it increased in other medical areas. The main increase in the share of publications was found in the areas of Zoology (from 0.57% to 5.03%), Nutrition Dietetics (4.65–8.09%), and the group of areas related to the environment (2.22–4.73%), some multidisciplinary areas not related to agriculture, and the humanities in general.

The identified increase in the number of publications in Zoology is associated with a shift in the share of publications on meat quality from the direction of Food Science Technology.

The revealed changes demonstrate a shift from the technology of obtaining meat and meat products and the microbiology of meat towards the problems of nutrition and the environment. In the health field, research into the carcinogenic effects of processed and red meat has become longer-term and more extensive. The current meat biosafety and health research is characterised by scale, duration, wider consumer coverage, and systematization of data from global databases. There has been an increase in research into links between meat and health other than colon cancer, coronary heart disease and T2D. The mechanisms of atherogenic and adipogenic effects, including those associated with intestinal microbiota, have begun to be studied more widely. Evidence is emerging of the impact of excessive meat consumption on the risk of cancers other than colon cancer, as well as other diseases.

Mapping of abstract and title terms in meat research publications also showed a significant increase in the contribution of Nutrition Dietetics direction. This cluster moved from the last fourth place to second in 2023 compared to 2013. The meat safety cluster, on the other hand, moved from first to fourth place. This reduction in the contribution of publications on meat biosafety is mainly due to a fairly detailed study of the chemical and microbial meat composition. However, this area of research still attracts intense interest due to the potential impact on consumer health and the possibility of the spread of antimicrobial resistance from meat microbiota. The U-shaped relationship between meat consumption and the risk of various diseases identified by many researchers may explain the inconsistency of smaller studies in this area. The possible explanation is the compensation of deficient nutrients with moderate meat consumption and an increased risk of some diseases with excessive consumption.

Nowadays, the progress in uncovering the mechanisms of possible harmful effects of meat on health is associated not only with the presence or formation of carcinogens during meat storage or preparation. Currently, negative effects of such natural components of meat as heme, L-carnitine, and glycolineuramic acid have also been discovered. The role of the intestinal microbiota of omnivores in transforming individual components of meat and harmful compound formation in the process of meat metabolism is under research. The influence of intestinal microbiota on the body can open up additional perspectives in elucidating the mechanisms of action of meat on the body. However, there are limitations in confirming the effects and uncovering the health mechanisms of excessive meat consumption due to the chemical heterogeneity of the meat consumed, highlighting the need for clear differentiation of meat composition in future studies. In our opinion, the opposite approach, used by a smaller number of researchers but demonstrating positive results, may also be effective, namely, not a long-term study of the health effects of increased meat consumption, but, on the contrary, studies of reduced meat intake in relation with general health status and outcomes of various diseases.

Interestingly, in 2023, as opposed to 2013, the main focus in the field of diet and consumer preferences is not on the nutritional properties of meat, but on the possibility of replacing meat with other products. The surge in scientific interest in reducing meat consumption and developing analogues and substitutes is primarily related to the environmental and health impacts of meat.

The number of environmental studies has increased significantly in recent years. Numerous studies and statistics have shown red meat's crucial contribution to global warming through methane production. The 28-fold potential for warming the atmosphere compared to carbon dioxide puts methane emissions from meat production at the forefront of the fight against global warming. However, there is not a very high consumer willingness to try and regularly consume meat substitutes and analogues, including cultured meat. Numerous opinion polls and searches for ways to influence the adoption of choices to reduce meat intake, especially red meat, which has the most pronounced global effect, highlight both areas with possible positive effects and various problems. The good potential has available information on the influence of meat on health, environment, or animal welfare. However, the groups of consumers willing to reduce meat consumption for some of these reasons vary greatly. Therefore, there is a need to target different categories of consumers. In general, animal welfare issues are less of a driver for reducing meat consumption compared to the carbon footprint and health impact of meat. According to various studies, natural plant protein is a better alternative for most consumers compared to cultured meat, insect meat, or ultra-processed plant-based substitutes. Nevertheless, any options for meat substitutes and analogues can have a certain effect on their consumer categories. However, there are serious concerns that the main consumers of meat substitutes and analogues may be people who already eat little or no meat. In this regard, the decisive factor in reducing meat consumption may be the development of diets and nutritious meals based on a combination of natural products that compensate not only the lack of proteins but also other nutrient deficiencies in both plant-based and meat-based diets.

Due to statistical studies showing excessive meat consumption in some populations and countries, a more effective long-term approach may not be to avoid eating meat completely but to gradually reduce the amount of meat per serving without raising serious concerns about malnutrition and lack of satiety. This approach is justified by the possibility of the gradual formation of the intestinal microbiome, which, in turn, has a pronounced effect on taste preferences and the feeling of satiety (Van de Wouw et al., 2017; Leung & Covasa, 2021; Barakat et al., 2024). Because of this, natural plant-based alternatives may be more effective than cultured meat, which is still meat and may have long-term health effects like regular meat without altering the consumer's gut microbiota. Studies of the microbiomes (not just the gut microbiomes) of healthy people who abstain from meat for a long time may also be useful.

Some researchers studying consumer preferences have shown the connection between the decision to reduce meat consumption and sociocultural norms and lack of information. Therefore, to help address global climate change, improve global health, and preserve biodiversity, it is necessary to strengthen comprehensive information about the possible consequences of excessive meat consumption.

It is also worth mentioning here certain results of humanitarian research in the field of meat, which have expanded recently and are related to the formation of the belief about the indispensability of meat in the diet. The decisive contribution to the insignificant empathy for animals is the separation of slaughtered animals and meat products in territorial, professional, psychological, and even linguistic terms (Buscemi, 2017; Thelle, 2018). The history studies since the Paleolithic era emphasise the role of culture in the legitimation of meat and show that "except under conditions of environmental scarcity, the meaning and value of meat cannot be attributed to intrinsic biophysical value or to the political-economic actors who materially benefit from it" (Chiles & Fitzgerald, 2017). In this regard, sympathy towards animals may be influenced by detailed information about the slaughtering process, on the one hand, and the presence of consciousness in animals of different systematic positions on the other hand (Andrews et al., 2024).

Thus, our research has revealed the main changes in meat research in the last decade. Much of the research has focused on the effects of red and processed meat. Replacing red meat with fish and seafood is a great way to improve health and a typical difference between Asian and Western diets. Unambiguous results on the consumption of white poultry meat are not yet available and its effects are to be determined. Further investigation is also needed for such specific areas as the long-term health effects of meat substitutes and the impact of consumer education on meat consumption patterns. Consumer awareness of all aspects related to the consumption of meat and meat analogues remains a decisive factor in addressing modern meat-related issues. The focus of each researcher on general trends in their work will contribute to the development of the industry in the context of contemporary problems of mankind and accelerate their solution.

Conclusion

The main part of the meat research consists of work aimed at improving the quality, safety and preservation of meat. On the other hand, evidence is accumulating on the negative health effects of high red and processed meat consumption such as increased risks of colorectal cancer, T2D, and cardiovascular diseases. The revealing of negative health effects of such natural and nutritionally important meat components as heme and carnitine (Bou et al., 2024; Koeth et al., 2013; Shahinfar et al., 2022) also requires a comparison of maximum permissible and required concentrations of these compounds. Additionally, the high production of methane by the livestock sector makes meat production a leading factor in global warming due to the characteristics of this gas. Concepts of well-being and consciousness in animals are also beginning to gain strength. In this regard, interdisciplinary approaches integrating environmental, health, and ethical perspectives are becoming especially relevant. Some studies in this area have already been conducted, showing that reducing meat consumption to the recommended healthy level (92 kcal per day) and avoiding meat from ruminants can almost halve greenhouse gas emissions (Steinitz et al., 2024). The main goal in the current years is not to increase meat production but to inform the population about the negative consequences of excessive meat consumption and provide the planet's population with the necessary nutrition against the backdrop of decreasing meat production. The highest priority research in the field of meat will remain developments aimed at meat authentication, which is also associated with the development of the segment of meat substitutes and analogues, as well as work devoted to reducing waste and greenhouse gas emissions from the industry. Priority will be given to areas of animal farming with the smallest carbon footprint. In the field of dietetics, a significant contribution to reducing meat consumption will be made by the creation of balanced diets based on plant products that provide adequate nutrition with reduced meat consumption or replacing red and processed meat with poultry and seafood. At the same time, the effects of poultry on health, as raised by some researchers, require more detailed research and confirmation. The most

promising studies in medicine will be those assessing not the health effect of increased meat consumption but, on the contrary, identifying the positive effects of reduced meat consumption, especially red and processed, on various diseases. Expanding research on the evaluation of consciousness of traditionally eaten animals could contribute significantly to not-meat consumer preferences provided that consumers are informed of the research results. Informing consumers about the latest research related to global problems is extremely important. Some information about the presence of consciousness in animals used for food could increase the level of empathy in consumers. The importance of information availability is noted by all researchers. It is especially important to provide such information about the health effects of certain nutrients, both those important to a healthy diet and those that are potentially harmful, as well as the content of these components in various foods. It is logical to place such information directly in the places where food products are purchased. Scientists often make significant progress in many areas, but results that are of public interest must be communicated to the public; otherwise, the impact of the research will be severely limited. Bringing research results to their end users is also an important task for scientists.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
Conceptualization, methodology, software, formal analysis, data curation, YO; writing—original draft preparation, YO, SM, EK, AZ, IK; writing—review and editing, YO, IK; project administration, AA. All authors have read and agreed to the published version of the manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflict of interest.

Author details
[1]Research and Production Center of Microbiology and Virology, Bogenbay Batyr Str., 105, Almaty 050010, Kazakhstan. [2]Kazakh Academy of Nutrition, Klochkov Str., 66, Almaty 050000, Kazakhstan. [3]Nutritest LLP, Klochkov Str., 66, Almaty 050000, Kazakhstan. [4]Al-Farabi, Kazakh National University, Al-Farabi Avenue, 71, Almaty 050040, Kazakhstan.

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