Meat and Muscle Biology™

Meat Quality Research Priorities: Outcomes From a Technical Summit

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Abstract: The goals of this article are to outline meat science research priorities, examine the current state of funding, and bring attention to the need for science-based solutions and innovation that maintains competitiveness for meat products while also addressing the talent pipeline of scientists and development of a workforce. It is the product of a meeting of meat scientists across disciplines and species. The meat industry is a cornerstone to modern society and has significant economic importance, with a global worth exceeding $1 trillion. The U.S. meat industry generates over $239 billion in income, supports 1.7 million jobs, and contributes $41 billion in taxes, while benefitting developed and developing nations through robust global trade. Central to the meat industry's success is the quality of meat products since consumers must have a desire to purchase and consume meat. Livestock and meat production face many challenges. Research efforts must continually increase efficiency, enhance sustainability, reduce climate impacts, address food security, and embrace artificial intelligence, machine learning, robotics, and talent development. However, efforts to impact these areas must also consider downstream impacts on meat quality or risk erosion of consumer satisfaction and demand for meat products. Thus, meat quality should be a fundamental component of all research concerning livestock and meat production, including poultry, small ruminants, and fish/seafood. Despite its significance, there is a troubling trend of decreased public funding for meat quality research in the U.S., posing risks to this essential food source and the development of future scientists. This article provides an overview of meat quality research funding priorities aimed at supporting a sustainable future for meat production, emphasizing the potential implications if funding does not align with these priorities. Furthermore, it highlights the risks to the talent pipeline and global competitiveness if adequate attention is not directed towards these critical areas.

Key words: meat science, meat quality, meat and poultry research, seafood research, research funding, meat sustainability
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Introduction

For the purposes of this article, the term "meat" encompasses skeletal muscle and its associated tissues derived from mammalian, avian, reptilian, amphibian, and aquatic species harvested for human consumption. Edible co-products consisting of organs and non-skeletal muscle tissues are also considered meat (Seman et al., 2018).

Addressing the quality, safety, affordability, nutrition, and palatability of meat involves navigating a multitude of challenges and opportunities. These include evolving and shifting dietary preferences, global economic dynamics, debates surrounding climate impact, regulatory frameworks, national and international policies, resource availability, advancements in genomics and microbiology, biosecurity considerations, policy implementation, and workforce-related issues.

Continuing to discover and research new processes, ingredients, and judicious use of resources is imperative for advancing knowledge and providing solutions to offering meat as part of a sustainable diet while constantly being mindful of societal needs and consumer preferences. At its core, research advances knowledge and trains scientists, which is necessary to continually solve evolving challenges. Research funding is necessary to make fundamental discoveries and find innovative solutions, while also enabling new scientists to be trained and developed for the future viability of the meat and food industry.

Meat quality encompasses both subjective and objective attributes, including attributes consumers perceive as important, such as food safety, organic, or animal production methods, (Schrobback et. al., 2023) and characteristics that are scientifically measurable (Becker, 2002), which makes assessments of quality broad and complex. Research funding for meat science and meat quality has declined over the past several years (Krehbiel, 2017). In a review of U.S. Department of Agriculture (USDA)-funded projects covering basic and applied meat research, only 6 projects were funded in 2023. Topics such as impacts of climate change on agricultural production, environmental sustainability, food safety, and the role of meat in the diet have historically been and are currently well funded by the USDA through the National Institute of Food and Agriculture (NIFA) and the Agricultural Research Service (ARS), the U.S. Department of Health and Human Services through the National Institutes of Health (NIH), and the National Science Foundation (NSF). However, *meat quality* research has not been, nor is currently, a priority for any funding agency. Previously, researchers in the discipline of meat science often obtained funding from the USDA Food Quality Program in addition to Animal Health and Production and Animal Products. However, in the USDA Fiscal Year 2023 Agriculture and Food Research Initiative (AFRI) Request for Application (RFA) for Foundational and Applied Science, the word "meat" only appears 6 times and only once as related to meat science research, with essentially no mention of post-slaughter factors that affect meat quality (USDA NIFA, 2023). The meat industry is the second largest manufacturing sector in the U.S. but receives a disproportionately low share of research dollars, emphasizing the need for increased investment.

Meat quality is an essential factor in any livestock production or meat-related research because it encompasses physical and chemical aspects that influence purchase decisions and eating experiences of consumers. It has been consistently shown that people consume meat and other animal products primarily due to high levels of eating satisfaction (Miller, 2020). In addition to eating satisfaction, consuming meat provides crucial nutrition—high-quality protein, essential fatty acids, vitamins, and minerals essential for human health. The desire to consume meat products underscores the importance of preserving and enhancing meat quality for individuals (and populations of individuals) to obtain adequate levels of nutrition. Research addressing meat production challenges will likely result in changes; thus, it is critical that research also ensures eating quality is maintained or enhanced. In addition, the cultural and social aspects of meat consumption, especially for many socially disadvantaged populations, are crucial. Eating high-quality meat products is an essential part of many cultures and should be an available source of nutrition for all people throughout the world. Access to meat not only provides a nutrient-dense food but can be a critical component for avoiding poverty, with the two concepts explicitly intertwined in many countries (Leroy et al., 2023; Zaharia et al., 2021; Siddiqui et al., 2020).

This article presents the contributions of meat (and meat science) to the U.S. and global economies, presents the state of funding for research on meat quality, and explores the potential impact that insufficient funding will have on research to ensure the availability of high-quality meat and meat products, as well as the development of future scientists and industry leaders. Change is needed to drive science-based solutions and innovation that maintains marketplace competitiveness while also addressing the challenges across the meat supply chain, including the talent pipeline.

Background

To organize, align, and prioritize meat science research needs, the American Meat Science Association (AMSA) gathered input from scientists with leadership experience in research, education, and policy. The AMSA represents all aspects meat science with a vision to be recognized for unmatched competence and commitment to attracting and developing the next generation of scientists and meat industry leaders and providing science-based meat research and information to various stakeholders. In 2023, the AMSA secured a conference grant from NIFA, which was used to form an adhoc planning committee of staff and researchers to plan a summit to discuss and reach consensus on meat quality research priorities. A group of 35 researchers and industry leaders representing a diversity of science expertise and experience convened to ideate, discuss, align, and prioritize meat quality research needs to support sustainable meat production in the future. The conference attendees received an initial charge from AMSA leadership, and then were separated into 3 working groups that addressed specific topics of adding value to meat, meat biochemistry, and meat merchandising value. Each working group had a discussion leader and recorder that kept track of the main discussion points. After approximately 8 h of working group discussion, the entire attendee group reconvened and had a broad discussion of research priorities. During the group discussion, AMSA staff recorded and cataloged the important and recurring points that came from each working group. The main and recurring points from the working groups are the foundation for the recommendations found in this article. The importance of the quality of meat underpinned all discussions, and consumer satisfaction was considered throughout the meeting. In particular, the committee sought to identify funding priorities broadly applicable to all potential funding entities, including USDA NIFA and USDA ARS as well as industry associations such as the National Cattlemen's Beef Association (NCBA), National Pork Board (NPB), National Turkey Federation (NTF), National Chicken Council (NCC), and the Foundation for Meat and Poultry Research and Education, plus other federal funding sources. This article provides a review of 1) economic, nutritional, and societal contributions of the meat industry; 2) current meat quality research trends; 3) emerging topics in meat quality research; and 4) challenges and opportunities.

Contributions of the Meat Industry

Economic value of meat

The meat industry is a significant contributor to global economic growth and societal well-being. According to a report published by the Food and Agriculture Organization of the United Nations (OECD-FAO, 2021), the global meat industry alone was valued at $897 billion U.S. dollars in 2021 and was forecasted to increase to over $1.3 trillion by 2027 (Figure 1, Shahbandeh, 2022) while employing many people worldwide. The meat, poultry, and seafood markets are expected to have a compound annual growth rate (CAGR) of 6.4% in 2027 valued at $2.07 trillion (Research and Markets, 2024).

In the U.S., the meat industry is the largest contributor of annual cash receipts among agricultural

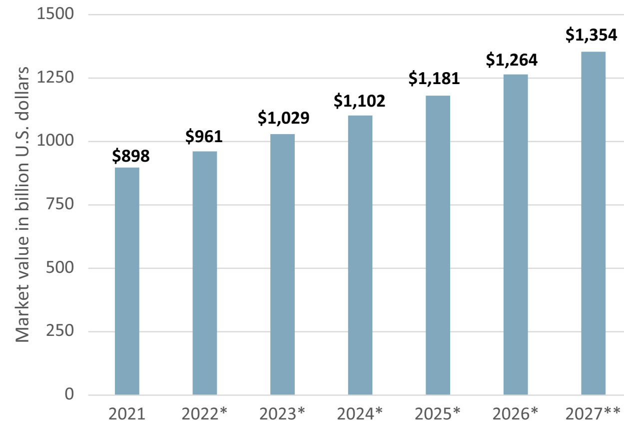

Figure 1. Global value of the meat industry in 2021 and forecast for 2022 through 2027 (in billion U.S. dollars). Source: Adapted from Shahbandeh, 2022. https://www.statista.com/statistics/502286/global-meat-and-seafood-market-value/.

commodities, and 2021 annual sales from meat and meat products contributed $433 billion to the nation's agricultural economy (USDA Economic Research Service [ERS], 2021). Furthermore, the U.S. meat industry is a significant contributor to household incomes by generating over $239 billion in salaries annually (NAMI, 2020). In terms of employment and supporting livelihoods, U.S. companies that produce, process, distribute and sell meat and poultry products employ as many as 1.7 million people nationally and generate an additional 4.3 million jobs in supplier and ancillary industries such as transportation, packaging, and marketing (NAMI, 2020) while contributing $1.221 trillion, or 5.67% of the GDP, to the U.S. economy. The meat industry employs about one-third (30.6%) of the total food and beverage workforce (Figure 2, USDA ERS, 2021). Beyond job creation, the U.S. meat and poultry industry and its employees pay over $45.33 billion in taxes, which is in addition to federal business taxes (Table 1, NAMI, 2020). The beef industry alone contributed over $60 billion to the U.S. economy (NCBA, 2023), while the poultry industry (including eggs) provided over 2 million jobs, $125.6 billion in wages, $555.9 billion in economic activity, and $33.7 billion in government revenue (U.S Poultry and Egg Association, 2022). Farming and processing sectors associated with pork production are responsible for supporting more than $35 billion in personal income and boosts economic activity in related services such as trucking, grain elevators, insurance, and other rural-based businesses (Cook and Schulz, 2022).

The projections for meat consumption appear robust based on USDA 10-y projections for the 2024–2032 period (Figure 3, USDA, 2023). The contributions of the meat industry are projected to remain strong, based

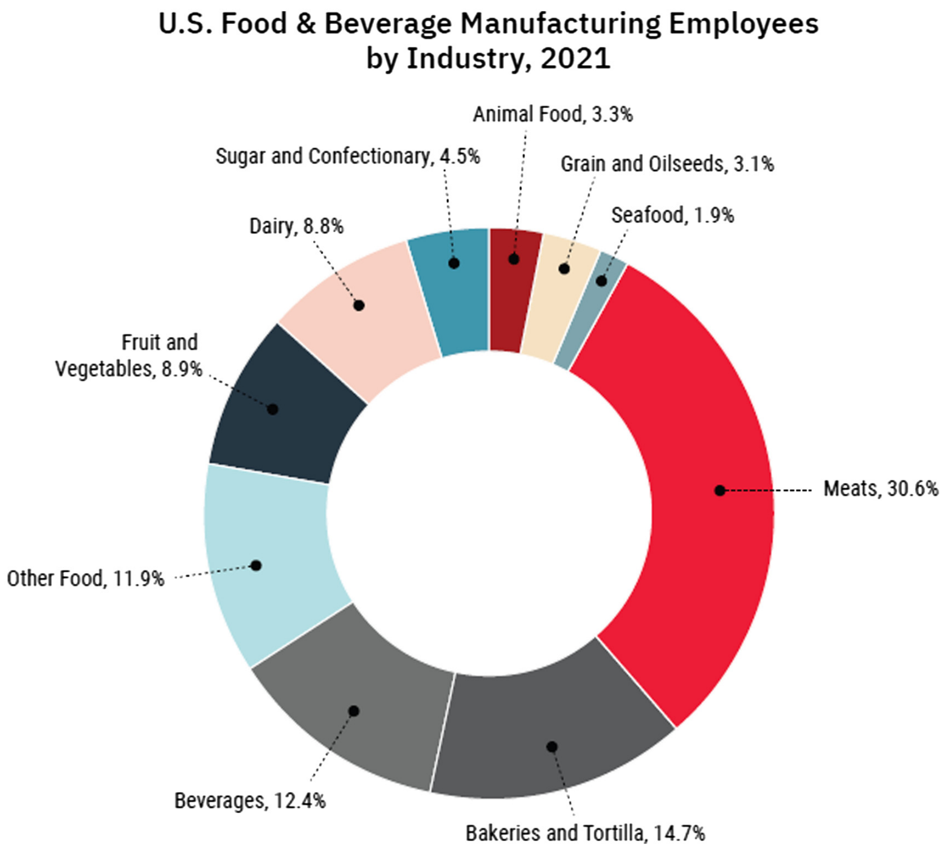

Figure 2. U.S. food and beverage manufacturing employees by industry, 2021. Note: Totals may not equal 100 due to rounding. Source: USDA Economic Research Service using data from the U.S. Department of Commerce, Bureau of Census, 2021 Annual Survey of Manufactures. Available at: https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/.

Table 1. Taxes generated in the U.S. by the meat and poultry industry (adapted from NAMI, 2020)

Tax Impact	Business Taxes
Federal Taxes	$63,887,826,000
State Taxes	$45,333,361,900
Total Taxes	$109,221,187,900

on consumption and projected demand. Globally, poultry, pork, beef, and sheep meat consumption are projected to grow 15%, 11%, 10%, and 15%, respectively, by 2032 (Figure 4), and the global per capita average demand for meat will increase by 2%, from the 2020–2022 base period to 2032. Poultry meat is expected to account for 41% of the protein consumed from all meat sources in 2032. Consumers in middle- and high-income countries are predicted to shift to cheaper meat and meat cuts due to revised spending priorities (Figure 5, OECD-FAO, 2023). These consumption projections counter any suggestions of emerging "meat avoidance" behavior and support the importance of advancing meat research (Tonsor and Lusk, 2022).

The U.S. meat industry also has a significant export market. The animals, meats, and products category of U.S. agriculture exports grew 22% from 2020 to 2021 with a value of $39 billion (USDA ERS, 2023). In 2022, the combined value of beef and pork exports alone was almost $20 billion (U.S. Meat Export Federation, 2022), and all meat exports combined are projected to increase by 2032 (Figure 4). Specifically, U.S. beef exports are expected to grow almost 15% from 2.9 billion to 3.3 billion lb. The U.S. is expected to maintain its position as the second largest pork exporter, behind the European Union, while poultry exports are expected to increase by almost 1 billion lb. by 2032. Competitiveness for export markets relies, in part, on processing efficiencies and meat quality, and both require ongoing research for continuous improvement to occur.

Nutritional value of meat

Meat supplies important nutrients, most notably the macronutrients protein and fat, and various micronutrients including vitamins and minerals, such as B_{12}, zinc, and iron (Figure 6). Several of these nutrients are critical to global health and well-being. Studies show that animal-sourced food consumption in low- and

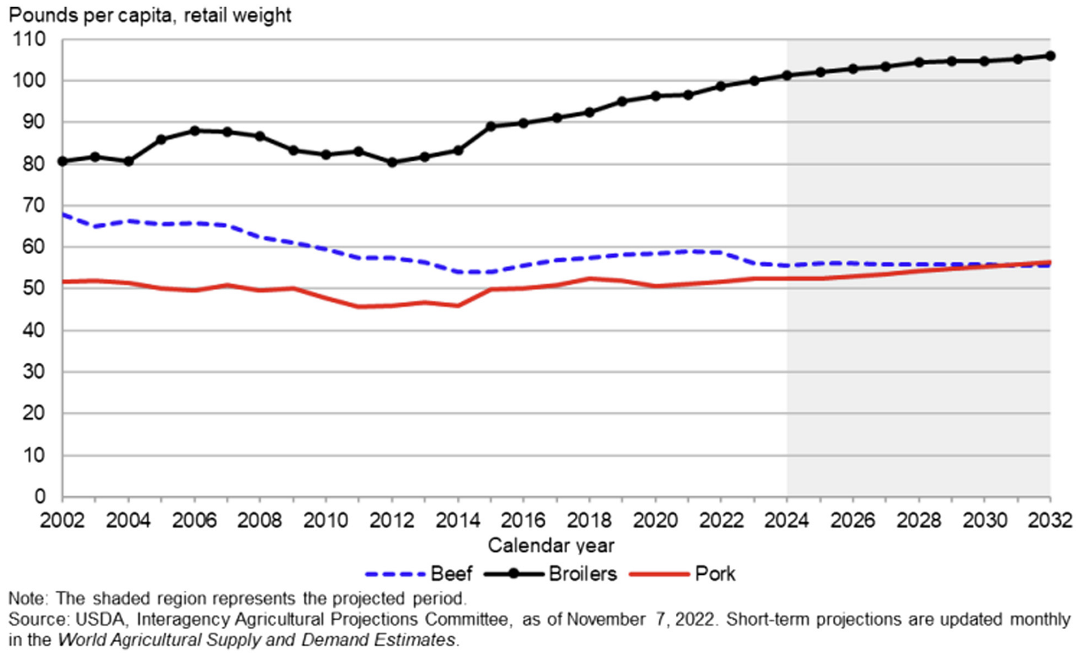

Figure 3. U.S. per capita meat disappearance, 2002–2032. Source: USDA, 2023. https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2032.pdf.

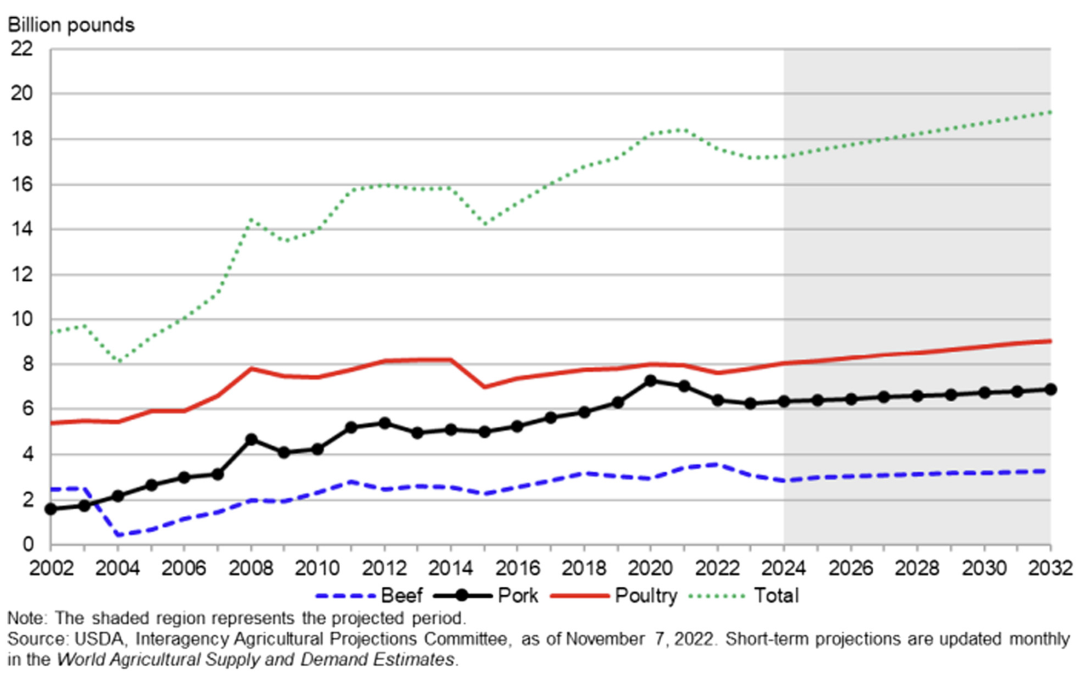

Figure 4. U.S. meat exports 2002 to 2032. Source: USDA, 2023. https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2032.pdf.

middle-income countries is positively associated with children's cognitive development, verbal ability, activity level, and behavior (Krebs et al., 2011). Nutrition contributed from meat, eggs, and dairy in the first 1000 d of life (conception through pregnancy to 2 y of age) impact quality of later life (Alonso et al., 2019). Critical micronutrients are an important consideration which may not always be easily or conveniently obtained with meat-free diets and are often already suboptimal in underserved segments of the world where access to fresh or high-quality frozen meat may be limited (Leroy et al., 2023; Zaharia et al., 2021; Headey et al., 2018).

U.S. meat exports have far-reaching potential for contributing to the nutritional stability of developing

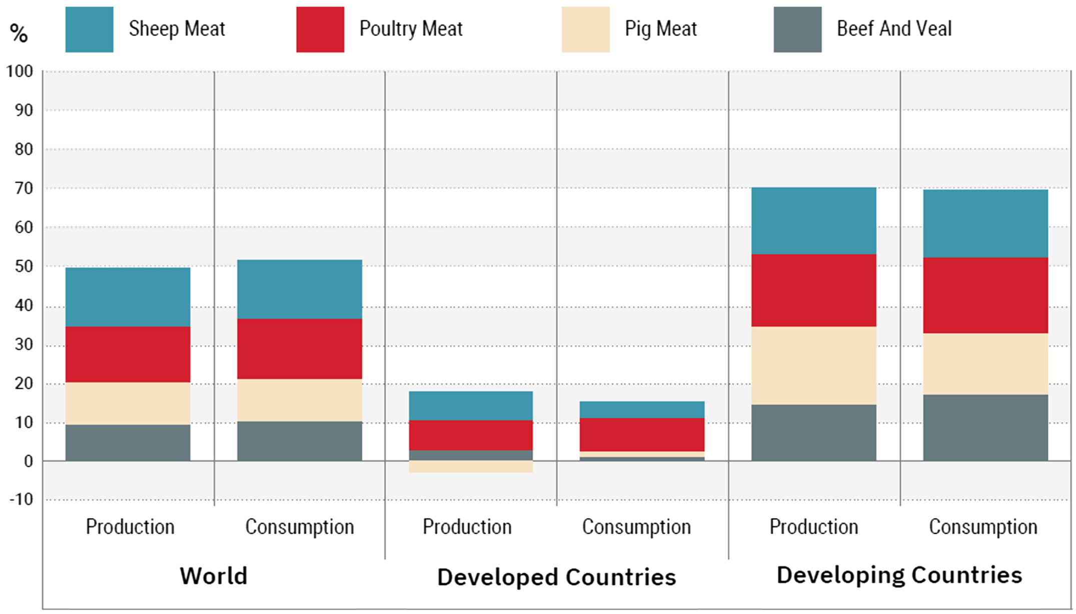

Figure 5. Projected global demand—Growth in meat production and per capita consumption on a protein basis, 2020–2022 to 2032. Source: Adapted from OECD-FAO, 2023. https://doi.org/10.1787/13d66b76-en.

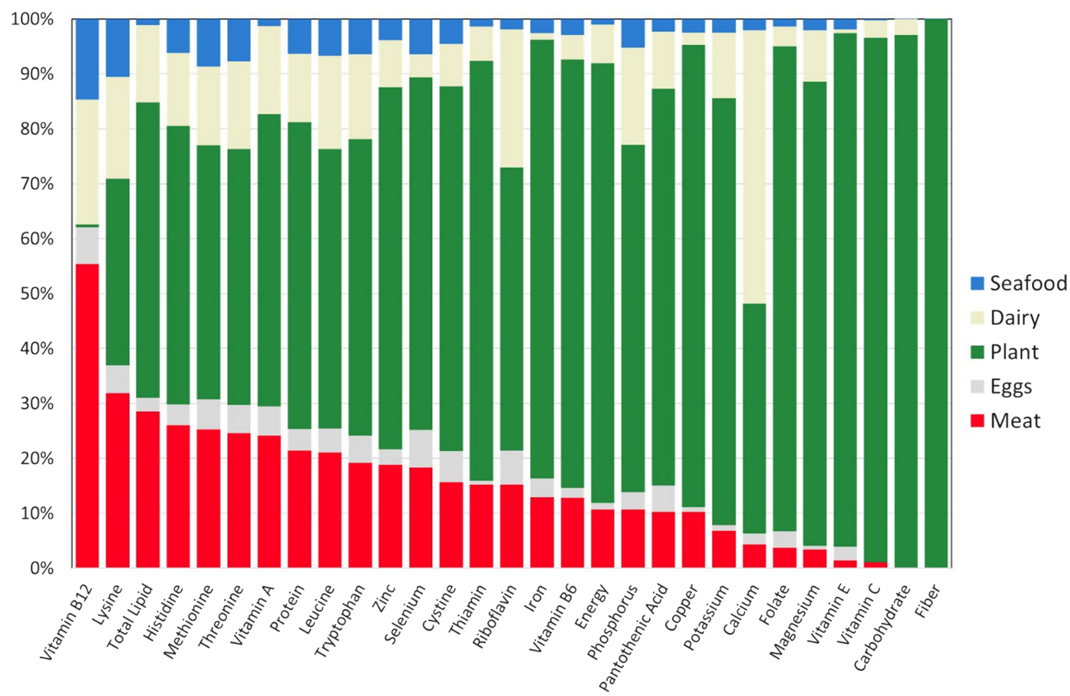

Figure 6. Nutrient contributions of food groups (Figure generated using data from the DELTA Model®). Note: The contribution of food groups to the global supply of nutrients and dietary fiber from food, with all forms of meat for human consumption (including organ meat and processed meats) highlighted. The values for protein and the indispensable amino acids have been corrected for bioavailability from the contributing food items, but not for minerals and vitamins (note that, e.g., the average bioavailability of iron and zinc in ruminant meat is 2 and 1.7 times as high, respectively, as that of pulses (Beal and Ortenzi, 2022). Adapted from Smith et al. (2022).

countries where access to other sources of protein may be limited. It is critical that high-quality protein from animal-sourced foods be available to potentially prevent stunting and other facets of malnutrition (Adesogan et al., 2020). In developed countries, meat is an important part of many people's diets and contributes to overall health and well-being, and there is growing evidence that it plays a key role as a nutrient-dense, highly satiating meal component (Morell and Fiszman, 2017).

The societal value of meat

Beyond economic and nutritional benefits, the meat industry also plays a critical role in society. The meat industry provides a source of cultural identity and tradition. In many parts of the world, meat is a significant part of local cuisine and social traditions. In discussing the societal role of meat, Leroy et al. (2023) highlighted that meat consumption is often linked to social occasions and celebrations, bringing people together and reinforcing cultural identity along with its critical role in human nutrition. In addition, livestock production is the main/only source of income for families in many areas.

That the meat industry provides a substantial contribution to both national and international economies, its value and significance are indisputable. Moreover, the meat industry's role in job creation, export markets, and nutritional security underscores its importance. Beyond economic and nutritional aspects, meat has cultural significance and many roles in fostering social connections and traditions.

Current Trends and Priority in Meat Quality Research

Meat quality research priorities—Outcomes of a research summit

There are several areas of focus for meat quality research. The meat science community recognizes the importance of production sustainability, reduction of utilized resources, climate change, and social change as major investment areas for research. A significant set of challenges facing meat science are to ensure that quality, eating satisfaction, and consumer acceptance of meat products are maintained as the other issues involved with livestock and meat production are also investigated. For U.S. consumers, taste, freshness, and safety are more important than price or other factors in meat purchasing decisions (Figure 7, Tonsor and Lusk, 2022). These factors are crucial to consider across all research priority areas outlined below. In these consumer surveys, the research priority areas were determined with the understanding that quality of meat, of which taste and freshness are major components, and its measurements would be foundational to all research and considered through all work (Tonsor and Lusk, 2022). Therefore, "meat quality" was not a stand-alone focus area but rather a consideration within all research areas and may be more heavily weighted in some priority areas.

The AMSA research priorities summit identified that meat quality research should be a component of funding for the following research priority areas: (1) resource utilization, climate impact, and sustainability; (2) food security, nutritional value, and food as medicine; (3) food waste; and (4) securing the future of meat science through talent, training, and technology (Figure 8).

The specific topics within these priority areas are expanded on below and focus on how research to address these priorities affect meat quality.

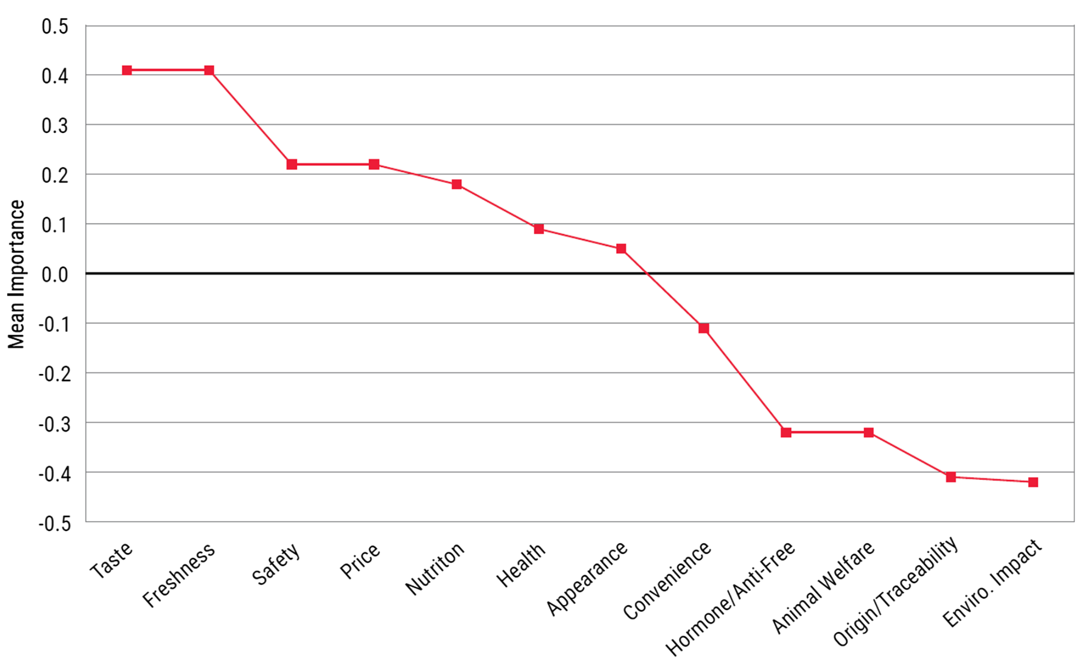

Figure 7. Factors influencing consumer meat purchasing decisions. Note: A higher Mean Importance value is more influential to a purchasing decision. Source: Tonsor and Lusk, 2022.

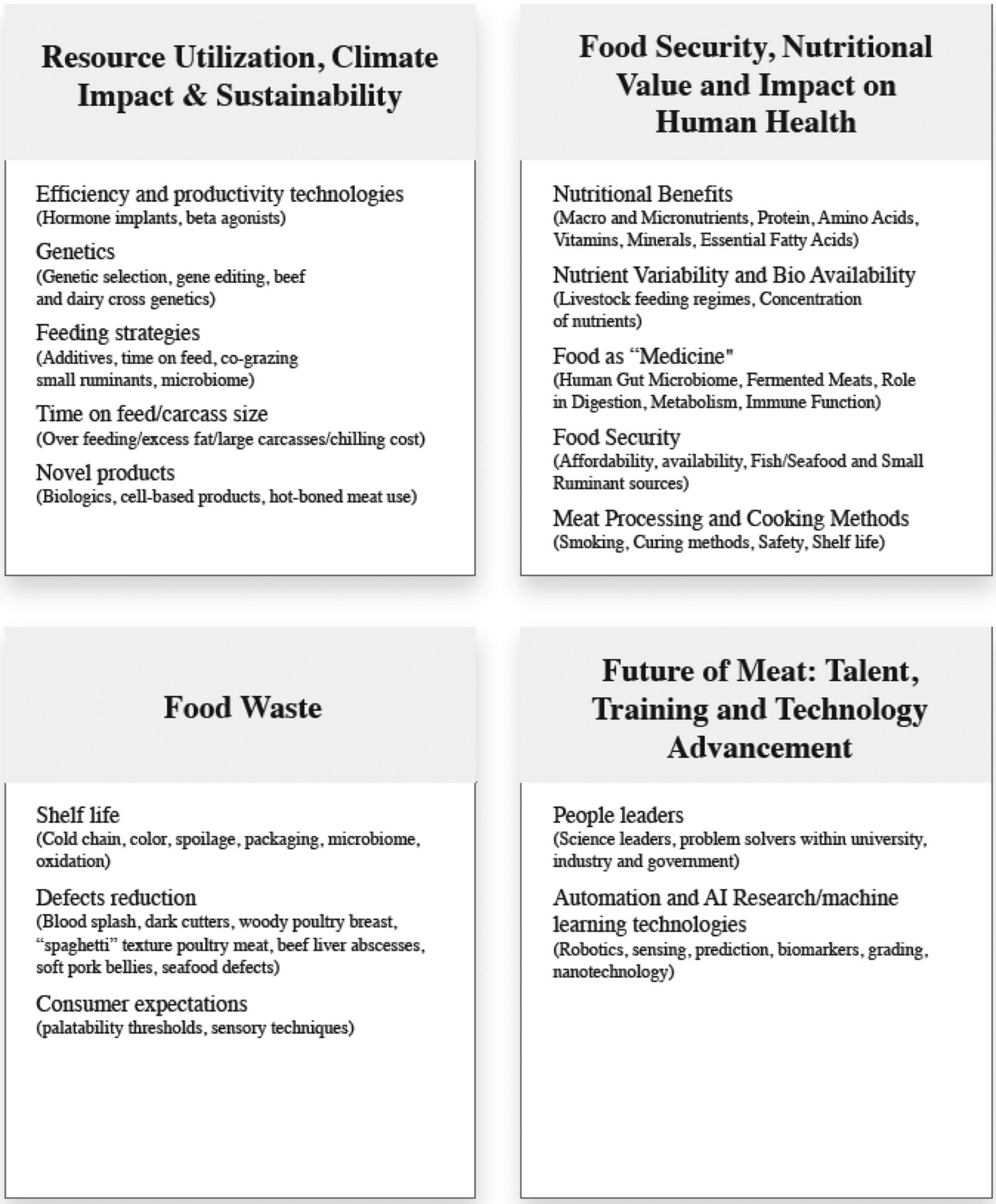

Figure 8. Research categories and specific priority needs. Research addressing these priorities significantly influences meat quality.

Resource utilization, climate impact, and sustainability

Efficiency and productivity technologies. As noted earlier, global demand for meat is projected to remain strong; therefore, meat science research is required in an effort to find ways to mitigate possible environmental impacts of meat production. Products, methods, technologies, ingredients, and strategies for raising livestock in a more efficient manner have the potential to impact the climate positively. The positive climate impact often comes from reduced feed consumption or reduced time on feed, which reduces the accompanying inputs such as water for growing crops for feed. Efficiency can also be accomplished by feeding regimes, nutrition and genetics that enable an animal to grow to harvest weight faster and/or with less feed. Maintaining affordability, being mindful of climate impact, and not impacting quality is the ongoing challenge, which requires research for answers and assurances.

One such example is animal growth technologies that enable livestock to grow more efficiently. Specific to beef cattle, hormone implants have been used in the industry for more than 60 y and improve growth rate and feed conversion of cattle (Smith and Johnson, 2020). The efficiency associated with anabolic implants has been shown to decrease greenhouse gas emissions from cattle by 8.9% and overall land use by 9.1% (Capper and Hayes, 2012), which can substantially lessen the environmental impact of beef production. This technology is valuable to sustain profitable operations and will continue to evolve. Hormone implants offer significant economic benefits to the livestock producer due to lower feed costs because the animal is much more efficient at converting feed to lean growth. This technology benefits the environment by reducing the resources needed to produce a pound of meat. The consumer benefits as that efficiency keeps meat prices affordable, but research on meat quality and carcass impact must continue as this technology evolves with new combinations and doses of hormones to optimize animal growth and meat quality (Johnson et al., 2013).

Genetics. Livestock farmers are constantly evolving practices and exploring new techniques that can include everything from diets to genetics to animal handling, all of which have implications for meat quality that need to be understood. Dairy cows serve a dual purpose of providing milk and beef via offspring that are not kept as breeding animals. In recent years, dairy farms have started breeding dairy cows to beef bulls, creating a genetic cross referred to as "beef-on-dairy" (McWhorter et al., 2020). Livestock managers increasingly utilize this strategy to optimize the value of the calf for beef, which helps reduce the environmental impact of meat production by reducing the number of beef cows needed to meet demand and produce a more efficient calf for beef production. Meat quality is an essential consideration in the beef-on-dairy crossbred strategy. Research has shown that meat from conventional dairy cattle is generally leaner than meat from beef cattle and the ribeye area is smaller than conventional beef. While this genetic and management strategy benefits the profitability of the farm by generating a meat producing calf with feed conversion and meat yield benefits contributed from the beef genetics, the meat quality is not negatively impacted (Foraker et al., 2022). Other research has shown the meat from beef-on-dairy crosses is more tender and flavorful than straight beef genetics (O'Quinn et al. 2016). The economic benefit to the dairy farmer for the adoption of this genetic "strategy" is that that value of the calf increases and contributes additional meat to the supply chain from a calf that would otherwise not have optimal meat quality or yield. The results of research in this area have led to increased implementation of beef-on-dairy breeding and demonstrate the importance of meat quality research in conjunction with livestock production changes. Another potential strategy for optimizing meat production that needs significant research is gene editing. Emerging gene-editing technology targets to reduce human and livestock diseases, and these initiatives are paving the way for this technology to become more mainstream in the livestock industry (Workman et al., 2023). Genetics and genomics can be used to optimize meat production and quality through genomic enhancements. For example, the woody breast condition in poultry can be addressed through genetics, as well as genetic influences on growth, muscle development, and quality (Zhang et al., 2021). Gene editing may also have ramifications on eating quality and meat color while addressing livestock production issues, such as disease. Meat scientists working in conjunction with animal geneticists can provide robust assessment of impact.

Feeding strategies, time on feed, and carcass size. The agriculture sector accounts for 10.6% of U.S. greenhouse gas emissions (EPA, 2021). Greenhouse gases are a contributor to climate change; thus, reducing any greenhouse gas is an emerging and growing area of interest to be accompanied by research on impacts to animal health and meat quality. Methane comprises 11.5% of all greenhouse gases in the U.S. and is more impactful at trapping heat in the atmosphere than CO_2 (EPA, 2021). Domestic livestock such as cattle, swine, sheep, and goats produce methane (CH_4) as part of their normal digestive process. The contribution of cattle, specifically, to the biogenic gas cycle due to their ability to digest grass is significant. Sustaining demand for beef ensures that grazing cattle play a vital role in beef production, contributing to regenerative agriculture and the biogenic carbon cycle. Research exploring various livestock production strategies such as feed additives or genetic selection for animals with low methane emissions (FAO, 2023) should include end-product quality. Reducing the use of water in livestock and meat production should also be considered in investigations.

The gut microbiome, which refers to the microbial communities that inhabit various digestive tract components of animals, also plays a crucial role in animal health, productivity, and environmental impact. Research has shown that feeding strategies, such as the use of probiotics and prebiotics, can alter the gut microbiome and reduce methane emissions from livestock (Carrazco, 2021). Probiotics are live microorganisms that can improve gut health, while prebiotics are non-digestible carbohydrates that promote the growth of beneficial bacteria in the gut. Therefore, research into feed strategies that improve the microbiome could help reduce the environmental impact of meat production while improving animal health and productivity and should be optimized for meat quality as well.

The general health of an animal is a crucial consideration in meat production, and the health status of an animal through its productive life has implications on meat quality. A healthy animal consumes a predictable and planned diet designed by nutritionists for desired carcass outcomes. When an animal is ill, consumption patterns change, and possibly the composition of the animal changes, which impacts meat quality. In addition, some illnesses require the use of antibiotics to treat the disease and avoid animal suffering. However, the overuse of antibiotics important to humans can lead to antibiotic resistance among animals and humans, which is a public health concern. Therefore, research into alternative approaches to disease prevention, such as vaccination and improved animal husbandry practices, could help reduce the reliance on antibiotics in livestock production.

Animal welfare and handling also play a crucial role in meat production. Improper handling and welfare practices can lead to stress, injury, and disease in animals, which can impact animal productivity and meat quality. Therefore, research into animal welfare and handling practices, such as the use of low-stress handling techniques, improved husbandry practices, and modernized housing conditions, could help improve animal health and productivity while reducing the environmental impact of meat production. Significant amounts of meat quality research have been conducted on the correlation of animal handling and undesirable meat conditions, specifically high-pH dark, firm, and dry (DFD) and low-pH pale, soft, and exudative (PSE), both caused by different degrees and timing of stress before slaughter. Beyond meat quality, research has led to understanding animal behaviors and to ensuring the utmost humane treatment of animals to the end of life. New stunning methods are continually being explored that reduce animal stress by rendering the animal quickly and humanely insensible, and the most recent significant change has been in adoption of carbon dioxide stunning for pigs (Channon et al., 2002).

Current production practices that emphasize meat quality, and especially quality grade in beef result in decreased feed efficiency at the end of the feeding period and cause significant amounts of excess fat that is trimmed off. Research is needed to determine what time on feed endpoint optimizes meat quality, so market signals do not encourage longer, inefficient feeding that produces excess waste fat. Production practices, especially for pigs and pork that emphasize growth at the expense of meat quality, specifically for the pork loin need to be addressed as pork loin value has continued to decrease relative to the rest of the pork carcass.

Current trends toward heavier animals as a means of efficiency for more output per head has created other issues that can impact meat quality (Wu et al., 2017). Heavier carcasses can have longer processing and chilling times, which can negatively affect tenderness and juiciness while also increasing energy input and costs. Research is needed for developing breeding and feeding strategies that optimize carcass size and reduce energy input are necessary while optimizing meat quality.

Livestock that have fulfilled their productive life of creating offspring are culled from the breeding herd but are an important contributor to the meat supply and food chain. Each has unique features and delivers meat quality differing from livestock bred and fed for strictly meat purposes. Research on optimizing the utilization of these animals can contribute more food sources or potentially new offerings if further studied. Sow meat, which is meat from a female pig that had at least one litter of piglets, are a more mature animal than market pigs and thus are typically sourced for hot-boned whole carcass sausage. New processing technologies could improve the utilization of culled sows and minimize waste. Bull meat is also from more mature male animals compared to market steers, and discovery-based research helped discover the important functional value of this mature meat, especially for sausage (Swan & Boles, 2002). Research is needed to enhance the purpose and value of the meat animal at every life stage to optimize each animal's contribution to the food supply.

Beyond the common sources of meat in the U.S., small ruminants, such as goats, sheep, and rabbits, or non-domesticated ruminants such as bison and deer, offer opportunities for new product offerings in the meat industry. Co-grazing cattle with small ruminants, such as sheep and goats, improves resource use and makes meat production more sustainable because they preferentially consume different plants commonly found in pastures (Pophiwa et al., 2020). Understanding consumer acceptance and education around these non-traditional animal proteins is important for developing successful marketing strategies. Additionally, creative solutions emerge with innovative technology being driven by goals in the U.S. to slow or neutralize global warming potential. An example is the installation of solar panels to generate energy, often to run livestock farms. A solution for optimizing growth of grass and weeds under the panels is to graze with goats. Raising practices must also be understood with these animals to have a holistic view of contribution and value. Further, the co-mingling of small and large ruminants can help reduce the environmental impact of meat production by improving pasture utilization and reducing the need for chemical fertilizers.

Novel products. Meat production is enhanced when all the products from slaughter and processing are utilized, and the greatest amount of value is obtained. The non-meat portion of livestock, referred to as byproducts or co-products, represents a large amount of value and is not always captured, especially by small and mid-sized processors. Approximately 10% of the value of cattle and 6% of the value of pigs is derived from co-products (Marti et al., 2012). Biologics are essentially molecules or tissues extracted from harvest co-products that could be repurposed for added value for animal or human health benefits. Research is needed to determine extractability, yield, and biological effectiveness amongst other attributes of these biologics. Therefore, research to optimize the benefits of small and large ruminant co-mingling is needed for this approach to meat production to be fully realized. Assessment of final product quality and consumer acceptance is always needed as new production models evolve. Basic or foundational research is also necessary when exploring innovative or novel areas to begin building a knowledge base.

Food security, nutritional value, and food as medicine

Meat, with its abundance of macro- and micronutrients, positively impacts nutritional status and well-being of the general public. While some potential negative health implications are associated with certain meat products and require ongoing exploration, it is essential to acknowledge and further research the positive nutritional benefits that meat offers, including those related to global food security. Beyond a rich source of protein, the essential amino acids, vitamins, and minerals in meat and seafood provide important macronutrients in the human diet, many of which are more bioavailable in these products when compared with plant-based meat alternatives. To better understand the role of meat in human nutrition, it is important to continue research on various aspects including its composition, impact of processing methods, and consumer perceptions, which impact consumption patterns and, therefore, personal health. The role of meat in global food security has long been recognized but takes on additional importance as the rate of the global population rapidly increases and climate change influences where and how crops and livestock are raised.

Apart from serving as a vital protein source crucial for the construction and restoration of body tissues, protein also plays a significant role in sustaining a robust immune system and in the creation of hormones and enzymes essential for bodily functions. The digestibility of proteins determines the degree of availability of amino acids and has been shown to be greater for meat compared to plant-based proteins. Further, cooking and processing of foods can affect availability of nutrients (Bailey et al., 2020) underscoring the importance of studying their effects on human health for informed dietary recommendations and interventions. Red meat is a rich source of essential fatty acids, including omega-3 and omega-6 fatty acids, which play a critical role in brain development and function, plus providing vitamins and minerals, including iron, zinc, and vitamin B12, which are essential for maintaining overall good health (Leroy et al., 2023). Many of these micronutrients are found in higher concentrations in meat compared to plant-based sources, and the ratio of these nutrients in meat can vary depending on the type of meat and the feeding practices of the animals. For example, grass-fed beef may have a different nutrient profile compared to grain-fed beef due to the nutrient variations of the feed types.

Because meat contains high concentrations of many essential nutrients per calorie, this makes it an important food for meeting the nutrient requirements of the body, particularly for those with increased nutrient needs, such as pregnant women, children, and athletes. Additionally, protein from animals is more efficiently absorbed compared to plant proteins (Pinckaers et al., 2023). Affordable, nutritionally dense foods are necessary for food security and public health.

There is growing interest in precision nutrition, the concept of "food as medicine" and balancing plant and animal-sourced foods. These dietary approaches involve tailoring diets to individual needs based on genetic, environmental, and lifestyle factors. Understanding meat as a tool for improving health outcomes and preventing diet-induced chronic disease and must consider the nutrient density and environmental impact of different food sources when making dietary choices. Funding research collaborations between public health specialists, nutritionists, medical professionals, and meat scientists would be powerful in accelerating an improved understanding of how meat could contribute to food as medicine.

Furthermore, collaboration between NIFA and the NIH is needed to understand how altering nutrient composition of animal-sourced foods can be used to prevent or treat diet-induced chronic human diseases. This area of study leads further into the need to understand the fate of foods during digestion and the microbiome of the human gut. The microbiome refers to the collection of microorganisms that live in the gut and play a vital role in digestion, metabolism, and immune function. Fermented meats, such as sausages and cured meats, can contain beneficial microorganisms that may promote a healthy gut microbiome. However, some epidemiological studies claim excessive consumption of processed meats can also have negative impacts on the microbiome. Research focused specifically on this potential causality is crucial, because perceptions and decisions with large implications are being made on epidemiological rather than evidence-based cause-and-effect studies regarding meat in the diet.

Impact of processing. The processing of meat can involve various steps creating finished products that meet consumers' needs and keep foods safe for reasonable shelf life. However, the term "processed meats" is misunderstood and misused, thereby creating confusion and leading to implications that it negatively impacts health. Research to verify the impact of processing on nutritional composition and digestibility of meat would be timely and useful as nutritional recommendations are being determined. For example, cooking methods such as smoking or curing, and grinding whole muscle cuts to form patties, are all forms of processing meat. Curing and smoking have been shown to improve amino acid absorption (Marušić et al., 2013), but the rate and degree of heating of proteins can affect specific amino acid availability in human diets and needs to be better understood (Bailey et al., 2020).

Defining "ultra-processed" is a topic for the entire food industry and may have implications for future dietary guidelines. Data from complete multi-disciplined research are needed to contribute to these discussions.

Seafood and fish. Seafood is also an important source of protein, omega-3 fatty acids, and essential nutrients, and a healthy contribution to diets (Hosomi et al., 2012). Seafood and fish research are important so that they meet consumer expectations while remaining affordable and because they are prominent sources of nutrition in many regions of the world. Advancing the understanding of nutritional components and bioavailability may differ for different populations. In addition, greater research focused on shelf life of seafood is important for the industry.

Food waste

Reduction of defects. Food waste not only is not only a loss of potential nutrition but also has an economic and environmental impact. Losses can be due to quality defects, such as discoloration, lack of storage life, low palatability, and other factors. One estimate is that the U.S. beef industry loses $3.74 billion annually due to discoloration. The discarded meat equates to 780,000 head of cattle wasted along with the resources to raise them (Ramanathan et al., 2022). The pork and poultry industry are both addressing muscle myopathies, ham halo effect, and woody breast, as examples, which cause product defects, discarded product, and loss of sales (Gonzalez, 2020). Poultry myopathies are estimated to cost the industry $200 million up to $1 billion (Kuttappan et al., 2016; Huang and Ahn, 2018). Research is necessary to find solutions to these issues and reduce economic losses and food waste. For instance, through improvements guided by research studies, the pork industry has been able to report significant improvements in consistency and quality of pork such as 2-fold improvement in subjective color scores since 2018 (Pork Checkoff, 2023). Desirable color increases purchase likelihood and decreases waste. Research to address wasted food potential can impact various areas of the meat industry including nutrition through available food otherwise wasted, improved cost of finished products, and reduced impact on the environment.

Quality optimization and defect reduction are important in the meat industry to ensure that meat products meet consumer expectations. This can involve addressing issues such as soft pork bellies in bacon, soft texture in seafood, or continuing to explore new methods for cutting a carcass into new meat cuts that meet consumer needs. The most recent Beef Quality Audit (NCBA, 2022) reported that $59/head was lost to various quality defects partly due to 28.5% of livers being condemned (as noted above), leading to large economic losses to the beef industry. Addressing meat quality defects and optimizing the full carcass use are both important to the industry.

An impactful example of the importance of cross discipline collaboration to address meat quality occurred as corn became more than a feedstuff. When corn began being utilized as a biofuel (ethanol, an alternative to non-renewable fossil fuels) a by-product stream was generated that became a new feed source for livestock. As has always been the case, diet impacts meat quality. In the instance of dry distillers' grains (DDG) being included in pig feed rations, the belly fat became softer, which negatively impacted quality and processing yield. When DDG were too high in the feed ration, the bellies were difficult to manage in processing, and the resulting bacon cooked differently (McClelland et al., 2012). Meat scientists at many institutions conducted research to fully understand the varying impacts of this new feed ingredient and ultimately provided data for the livestock industry to guide inclusion rate limits so the highly valuable pork product (the belly) could continue to be converted to quality bacon without adding cost to processing. Meat scientists continue to collaborate with feedstuffs providers as they adapt to pressures and opportunities such as use of climate resilient grains and also byproducts of biofuels as they also work to provide environmentally friendly renewable energy fuel.

Shelf life. Color is one of the critical factors that influences meat quality and shelf life (Ramanathan et al., 2022). Meat discoloration is a common issue that results from a range of factors, such as oxidation, lipid oxidation, microbial growth, and enzymatic reactions. Developing strategies to improve meat color stability and minimize the formation of undesirable pigments will minimize the waste of food that did not sell, due to color alone. Color is such a critical variable to determining meat quality that a Meat Color Guideline was developed and published to guide research by the meat science community (King et al., 2023). The necessity for extensive and detailed guidelines when conducting research on this one attribute (color) is testament to the rigor and research required to maintain quality of meat and subsequent consumer demand.

Another factor impacting shelf life is microbial stability. Because microbial growth can impact shelf life, rapid detection methods are critical to identify specific microorganisms that cause spoilage, color, and off-flavor problems, especially in comminuted products. Traditional microbiological methods are time-consuming and require expertise, while rapid detection methods can provide results in a few hours, aiding in informed decision-making which may keep food from entering the waste stream due to reduced shelf life. The research areas of microbial testing to ensure safe food and adequate shelf life are crucial to public health and a sustainable and consistent meat supply. Numerous bacteria can reduce the shelf life of meats, leading them to be discarded or reduced in value. Researchers are constantly challenged to find strategies that better identify and control microbial populations in meat production systems. Sanitary practices throughout production and processing plus equipment design are both critical areas to include in this research area.

The development of new packaging materials and technologies can improve shelf life, reduce spoilage, and minimize waste. Packaging continues to be an area of innovation and also critical to consumer purchasing decisions. Not only must packaging be functional to provide physical and biological protection, but it must be eye appealing and sustainable for consumer acceptance. Collaborations between engineers, chemists, microbiologists, social scientists, and meat scientists are necessary to assess the performance of new packaging materials. Films delivering antimicrobials to inhibit microbial growth, for instance, continue to be a critical area of discovery. Shelf life and product formulation research are important for maintaining the quality of meat products and consumer acceptance.

Consumer demand for single-ingredient foods or simple ingredient statements poses challenges for maintaining a reasonable shelf life of meat. Many ingredients serve as antimicrobials and their removal can shorten shelf life leading to wasted food before it gets through the supply chain to consumers. Methods to keep meat safe and with a reasonable shelf life continue to be explored. For example, natural curing with celery powder or arginine is one method to generate nitric oxide as part of producing a shelf stable product that is visually appealing and meets consumer expectations (Modrow and Osburn, 2020; Posthuma et al., 2018).

Maintaining proper temperature control is critical to preserving the quality and safety of meat products. Focusing on developing new technologies to monitor and maintain the proper temperature throughout the meat supply chain will minimize loss due to shortened shelf life or loss due to cold chain failure. Temperature control is also important to minimize protein and lipid oxidation. Oxidation is a chemical reaction that occurs when meat is exposed to air, which can result in changes to product characteristics. While some oxidation is normal during the cooking and storage of meat, excessive oxidation can lead to the formation of compounds, such as free radicals, that impact taste, tenderness, color, and other meat attributes (Honikel, 2009).

The waste of food (and of resources) can also occur during the various processing steps of meat. Water is imperative for cleaning, sanitation, and other steps in slaughter. The volume of wastewater can have environmental implications if not reclaimed. Research needs include developing sustainable methods to treat, recycle, and manage meat processing wastewater. Research is important for meeting environmental regulations but also for microbial safety for reuse in other purposes at the facility. Carbon dioxide is commonly used for chilling meat formulations for purposes of handling or forming into processed products. Developing sustainable methods to capture and reuse carbon dioxide would help cost and the environment.

Meat products can have imperfections from natural causes or created from missteps in processing or animal handling. Continually working to reduce these imperfections by understanding the biomechanisms can help correct or mitigate the defect that can affect marketability to the consumer. Examples include woody breast in poultry, mentioned earlier, and blood splash in neck region muscle due to improper exsanguination, and dark-firm-dry meat and pale-soft-exudative meat are examples of defects that require additional research to better understand the cause so they can be prevented or so ways to utilize the meat in alternative products acceptable to consumers can be found. Managing biological variability of the live animal and processing variability of the meat are the starting points.

Co-products, also known as offal, refer to the internal organs and entrails of an animal. Co-products are a valuable source of nutrients, serving many purposes that add value to the overall carcass, such as biomedical products or pet food. However, co-products can also generate waste if not utilized efficiently. Smaller processors may not have opportunities to optimize co-products' use and could benefit from newly identified revenue streams and products. The development of new edible products and biologics, plus growth of export markets will drive value of the whole animal, which keeps cost to consumers more affordable and improves overall sustainability of meat production. These products also have expectations of quality from consumers and defects must be minimized. Beef-on-dairy crossbred cattle have a higher incidence of liver abscesses (Nagaraja, 2023). The cattle are often treated with antibiotics to reduce abscesses and ensure good animal well-being but leads to the research need to identify antibiotic alternatives for treatment or methods to reduce reliance on antibiotics as a treatment method to reduce the risk of developing antibiotic resistance (Reinhardt and Hubber, 2015).

Disposal of all types of non-edible product streams from processing facilities may or may not be considered waste, depending on the ability to create a purpose or value. Averting some streams from landfills, such as through paper recycling, has an environmental value. Repurposing or finding use for other waste steams may create economic values, such as some pet treats. Innovation in the input and output streams, as well as within, processing facilities can provide sustainability benefits for the business and environment (Shirsath and Henchion, 2021).

The future of meat: Talent, training, and technology advancement

Leadership and labor force development. There is a critical shortage of individuals with basic and applied training that are needed in the future to fill important roles at USDA and in other government departments and agencies, faculty, and university leadership positions as well as a myriad of industry positions. With the continued strong demand for meat products worldwide, significant challenges related to labor availability and creating a highly skilled workforce need to be addressed. Recently launched workforce development programs, funded at the state and federal level as part of the American Rescue Plan (USDA, 2022), are a positive step in addressing part of the challenge. Some examples include the Meat Mastery Program offered at Oklahoma State University (Oklahoma State University, 2023) and University of Nebraska–Lincoln (University of Nebraska, 2023). The number of students from agricultural backgrounds is continually shrinking; thus, we must recruit non-traditional students into the meat science discipline. This will require reaching out and engaging with a more diverse segment of students to generate interest in the many opportunities to make a difference in the world by enhancing food security, human health, and sustainability through livestock and meat. The diversification of the workforce will require future training and education in various fields. Those who engage with problems, new concepts, and solutions during the research phase will arise as leaders and pioneers in advancing new and emerging technologies. The foundation for developing the pipeline of future leaders in industry, academia, and government is training provided by graduate research experiences. The National Needs Fellowship Program (USDA NIFA, 2024a) is an example of support for training of scientists through research projects.

Emerging Topics in Meat Quality Research

Automation and artificial intelligence

Automation and engineering include modern processing and manufacturing technologies, such as artificial intelligence (AI) and machine learning, robotics, nanotechnology, and remote sensing. These technologies can be used to predict yield and quality, which can lead to the greatest utilization and value of meat as well as reduce labor costs, improve safety, and increase process efficiency. Robotics, engineering, and automation will help ease labor shortages, but significant investment in equipment and the skills to develop and operate these technological advancements will be needed. AI is quickly evolving, and understanding the potential may ease some of the challenges faced by the meat industry such as enabling automation and improving efficiency in production processes. AI can optimize tasks such as sorting, grading, and packaging meat, leading to increased productivity and reduced labor costs. A vast amount of data is generated throughout the supply chain, from production to distribution and consumption. Biostatistics with AI and machine learning models to analyze these data can help identify trends and patterns that can inform decisions related to production, distribution, efficiency, and even food safety. A skilled workforce with expertise in data science and analytics is needed to analyze these data and extract important insights.

New technologies

Determining meat quality requires measurements, tests, and standards upon which research can be based. Biomarkers are measurable indicators of meat quality and can provide information on freshness, tenderness, and flavor. Research should focus on identifying new biomarkers that accurately predict meat quality and stability. Having sensory feedback (human and machine) is critical for determining the impact of changes in the meat production system, from live animal through to consumer. New methods and new sensory technology must continue to be assessed and evolved to provide qualitative and quantitative responses to better understand the impact of variables on the final product. Understanding consumer expectations and limits for key attributes such as tenderness, color, or juiciness are important in the meat industry. Surveys can be used to gather information about consumer preferences and help guide product development.

Beyond government funded, independent research is the opportunity to collaborate and partner with other systems related to food and agriculture such as bioengineering. Cell-cultured meat may fall into this area and exploration of this frontier is important to meat science for understanding cell growth, processing steps, consumer views, food safety, regulation and labeling compared to traditional meat. Expanding public-private partnerships must continue as a means of accelerating research, and students must be involved to expose and advance basic principles of meat science toward solutions and toward new ideas for the future of meat.

Challenges and Opportunities

Status of research funding

USDA NIFA. Research on meat quality has received funding from various sources including competitive and foundational funds from the USDA. Grant funding for meat quality through the USDA is typically directed through NIFA and is found in the AFRI request for proposals across different research priority areas such as food quality, novel foods, and animal growth and product quality. NIFA-AFRI programs have played a historically significant role in funding meat science research and supporting graduate training for future leaders in meat science across industry, academia, and government. However, AMSA scientists and researchers are concerned by the recent trend of decreased funding for overall U.S. agricultural research (Figure 9) (USDA ERS, 2022) and by the decline in number of meat-related projects funded. In a review of research grant awards over the past 2 decades and across priority areas, projects focused on meat have declined, and the priority areas typically funding meat research appear to have shifted focus. The data show the following:

- The A1361 Improving Food Quality program funded 13 projects worth $4,460,629 between 2016 to 2018 but saw a combined reduction of over $900,000 in total program funding in that period and then the program was eliminated in 2019.
- Novel and Innovative Foods (A1364) funded 8 meat-related projects between 2020 and 2022 totaling $3,319,704. Only 4 of those grants were solely on meat quality for $1,657,954. The others had either heavy engineering or human health concepts.
- The Novel Foods area has directed more funding toward meat analogs, $4,305,787 across 8 projects, with 6 of the 8 awarded to one institution.
- The Food Manufacturing priority area had been another area of potential funding for meat researchers, but no grants were funded in this area during 2017–2018.

The elimination and/or shift in priority areas leaves few options for meat quality research funding (Table 2, USDA NIFA, 2024b). Previously, researchers in meat science often obtained funding from the Food Quality

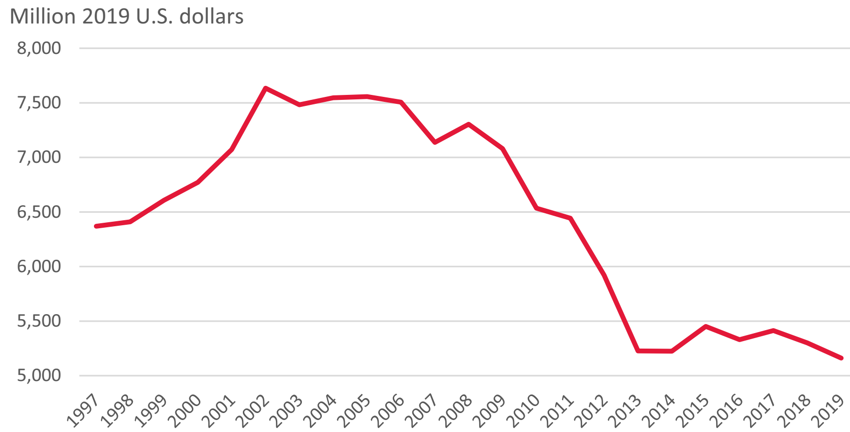

Figure 9. Total public funding of agriculture and food research and development in the U.S. 1997–2019. Source: Adapted from USDA Economic Research Service (2022). https://www.ers.usda.gov/data-products/agricultural-and-food-research-and-development-expenditures-in-the-united-states/.

Table 2. Trends in competitive grants funding in meat quality research[#] through two priority areas in the USDA NIFA AFRI Foundational and Applied Science Program during 2016–2022 (adapted from USDA NIFA, 2024b)

Fiscal Year[Ψ]	Program area priority code	Total number of research grants funded	Number of meat quality research grants funded	% of total number of grants funded in meat quality research	Total funding amount	Meat quality research grants funding amount	% of total funding amount to meat quality research
2016	A1361	17	5	29%	$6,079,213	$1,816,746	29%
2017	A1361	17	4	24%	$5,359,672	$891,651	17%
2018	A1361	16	4	25%	$5,386,818	$1,752,232	33%
2019	A1364	17	3	18%	$7,765,862	$1,399,000	18%
2020	A1364	16	1	6%	$6,765,923	$199,389	3%
2021	A1364	25	4	16%	$11,921,247	$1,657,260	14%
2022	A1364	28	3	11%	$13,319,423	$1,188,505	9%

[#]Research on post-harvest aspects of skeletal muscle as food, including postmortem muscle biochemistry and meat processing.

[Ψ]The upper limit for grants was $500,000 in fiscal years 2016–2020 and was increased to $650,000 in fiscal years 2021–2022.

A1361 = Improving Food Quality (2016–2018; 3 years)

A1364 = Novel Foods and Innovative Manufacturing Technologies (2019–2022; 4 years).

Program in addition to Animal Health and Production and Animal Products.

AFRI was established by Congress in the 2008 Farm Bill and re-authorized in the 2018 Farm Bill. The program was re-authorized to be funded at $700 million a year. The Consolidated Appropriations Act of 2023 funds AFRI at $455 million. NIFA provides AFRI grants to support research, education, and extension activities in 6 Farm Bill priority areas: 1) Food Safety, Nutrition, and Health, 2) Animal Health and Production and Animal Products, 3) Agriculture Systems and Technology, 4) Agriculture Economics and Rural Communities, 5) Bioenergy, Natural resources, and Environment, and 6) Plant Health and Production and Plant Products.

AFRI-funded science is vital to meeting food, fiber, and fuel demands as the world's population progresses toward a projected 10 billion by 2050 concomitant with diminishing land and water resources and increasingly variable climatic conditions. AFRI programs also are crucial for developing new technologies and a workforce that will advance national security, energy self-sufficiency, and the health of Americans (USDA NIFA, 2024c). Within AFRI, 13 meat-related projects were funded in 2016–2018.

NIFA's AFRI funding portfolio includes both single- and multi-function research, education, and extension grants that address key problems of national, regional, and multi-state importance. AFRI-funded projects sustain all components of agriculture, including farm efficiency and profitability, ranching, renewable energy, forestry (both urban and agroforestry), aquaculture, rural communities and entrepreneurship, human nutrition, food safety, biotechnology, and conventional breeding. These projects also create jobs and help develop the next generation of agriculture and food scientists.

The AFRI portfolio includes Coordinated Agricultural Projects (CAP) and Food and Agricultural Science Enhancement (FASE) grants. CAP grants are large, multi-million-dollar projects that often involve multiple institutions. FASE grants help institutions become more competitive and attract new scientists and educators to careers in high-priority areas of agriculture.

In the Fiscal Year 2023 RFA for Foundational and Applied Science, the word "meat" only appears 6 times and once as related to meat science research, with essentially no mention of post-slaughter factors that affect meat quality (USDA NIFA, 2023). The livestock and the meat industry stand as dominating economic forces in American agriculture, constituting the largest sector. Remarkably, the meat industry, holding the position of the second largest manufacturing sector, commands a disproportionately low share of research dollars, emphasizing the urgent call for increased investment in this vital area.

Other funding sources. Research on meat quality has received support from various USDA programs, such as the Sustainable Agricultural Research and Education program, Small and Family Farm, and others. USDA ARS funds research on quality of red meat, poultry, and seafood, subject to annual congressional appropriations. Additionally, federal funding for meat quality studies has been granted by Health and Human Services via the NIH, the NSF, and the Department of Defense, among others.

While industry sources like commodity check-off programs or trade associations have historically funded meat quality research, diminishing funding levels over time have coincided with decreased program receipts. Private funding from meat processing companies, equipment suppliers, ingredient manufacturers, animal health, and meat marketing companies is available, but the resulting research findings may not always be published and shared to advance the science of meat quality. Finally, the USDA Agricultural Marketing Service has implemented a program offering technical resources to meat processors on crucial quality aspects like creating value-added products, marketing, and quality assurance but did not include research funding.

A historical review of U.S. public meat research funding between 1980 and 1997 (Miller, 2002) showed the proportions directed toward meat quality, food safety, and product development. Meat quality had the highest proportion of funding until 1995, after which food safety was more prominent. Not only does this show the history of commitment to meat research, but also it demonstrates the responsiveness to public concerns about emerging foodborne pathogens at the time, which were associated with animal products and human illnesses. Decades of fundamental, basic, and applied meat science research has had a profound impact on food security, food safety, and product quality. A few examples (Table 3) highlight the importance of research, some foundational and contributing to global practices and others demonstrating the need for immediate investigation and solutions to maintain a consistent meat supply.

The concern for the future of meat science research extends beyond the U.S. A comprehensive report on the future of meat science by the year 2030 provided results and conclusions based on an international survey of people and groups involved with meat research. Among the conclusions were that "a strong universal consensus exists that the meat industry and research community face serious threats that must be urgently addressed" and that diminished resources, the closure or reduction of major meat science entities, and a

Table 3. Historically impactful meat quality research examples

Example 1	The fundamental research funded by USDA AFRI in early 2000 helped understanding of mitochondria's role in beef color. The knowledge gained from those studies was instrumental in designing modified atmospheric packaging currently used by meat retailers and using oxygen scavengers commonly included in meat packaging during shipping to preserve quality. A review of the work can be found in Ramanathan and Mancini (2018).
Example 2	Abnormal postmortem muscle metabolism in pork carcasses resulted in large economic losses due to the prevalence of pale, soft, and exudative meat (Brewer and McKeith, 1999). Fundamental research in muscle metabolism determined the factors, including genetics, feeding, and animal handling, that caused quality defects, and genetic selection and production practices decreased the incidence of quality defects in pork (Hamilton et al., 2003) and almost eliminated the condition that led to meat waste.
Example 3	Woody breast myopathy is a major concern affecting the palatability and processing characteristics of chicken breast. Understanding the causes and developing interventions that improve chicken breast quality are essential to ensure palatability of and demand for chicken (Ahmed et al., 2021). Correcting the causes of the undesirable muscle tissue condition helps ensure a positive eating experience for consumers and reduces meat waste.

critical decline in expert personnel due to retirements and low replacement rates are key challenges facing the field (Polkinghorne, et al., 2022). Additional perspective on the topic was provided in Animal Frontiers (Polkinghorne et al., 2023) outlining the depth of the challenges, such as the closure of the Meat Research Institute (Bristol, United Kingdom) in 1990 and MIRINZ in New Zealand both due to lack of funding.

Training future scientists and problem solvers

The training of new scientists is crucial for providing leadership, technical support, advancements, research and development, quality assurance, and meat safety. In 2023, AMSA membership reflected 214 academic researchers affiliated with various universities, which were training 213 graduate students and postdoctoral researchers to meet the industry's need for scientific and technical support. Additionally, programs at community colleges and high schools, many that were established post-pandemic, further support the need to address supply chain issues and increase local meat production. Meat science is a well-established discipline at the intersection of animal and food science and is an important part of ensuring the availability of high-quality meat. The growing number of members of the AMSA attests to the importance of meat science, not just in a research or academic setting but with companies involved in global food production. Graduate student training through research projects provides the pipeline of future industry, academia, and government leaders.

As research to address the challenges in meat production progresses, the quality of the final product must always be considered, as it is a key factor driving ultimate demand for meat products. The trend of decreased funding for meat quality research will result in negative implications for the future of a critically important food source, the industry's economic impact potential and development of future scientists and industry leaders.

The implications of continued underfunding of meat quality research are numerous. Suggestions to address and change the trajectory include the following:

1. Granting agencies should include meat quality–specific language in current and future funding opportunities.
2. Granting agencies should increase and prioritize funding for meat "quality" research within the existing programs by revaluating areas where meat quality research is an important component of high-priority issues and increasing investment as funding is available.
3. Granting agencies should prioritize meat quality research as appropriate by including language from this report when implementing future Farm Bills.
4. Ancillary research related to meat quality should become an integral part of existing appropriate programs.
5. Federal agencies should fund interdisciplinary research related to meat, including areas such as engineering, food safety, economics, human nutrition, and food as medicine.

Conclusion

An impactful opportunity exists for policy makers to increase funding for, and prioritization of, meat quality research and to provide greater access and availability of funding for these critically important topics. There is significant risk associated with historically underfunded research in meat quality, and if this challenge persists over a long period of time these impacts will be seen throughout the animal agriculture industry. Holistically, a paradigm shift is needed to drive innovation and value creation to continue to provide a sustainable, nutritious food source, grow the talent pipeline, and maintain global competitiveness of this important industry.

It is vital for those involved in the agricultural industry to recognize the impact of consistently underfunding meat science research, a fact that should be echoed in industry talks, policy making, and discussions with key players. Meat science is not just a niche; it is essential to our global food chain, and research institutions, their infrastructure, and these programs rely on federal funding support as well as funding from industry partners. Underfunding has far-reaching consequences, affecting not only the meat industry but also broader areas like livestock sustainability, climate impact, food security, and waste reduction. As outlined in this document, funding is most critical to 4 areas: 1) resource utilization, climate impact, and sustainability; 2) food security; 3) food waste; and 4) technology and training for the future of meat, while recognizing that meat quality is a critical component of all the research priority areas. This recognition is essential to maintain the global leadership of the U.S. as one of the largest producers, consumers, and exporters of safe, affordable, high-quality meat products.

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Literature Cited

Adesogan, A. T., A. H. Havelaar, S. L. McKune, M. Eilittä, and G. E. Dahla. 2020. Animal source foods: Sustainability problem or malnutrition and sustainability solution? Perspective matters. Glob. Food Secur.-Agr. 25:100325. https://doi.org/10.1016/j.gfs.2019.100325

Ahmed, M. R., D. D. Reed, Jr., J. M. Young, S. Eshkabilov, E. P. Berg, and X. Sun. 2021. Beef quality grade classification based on intramuscular fat content using hyperspectral imaging technology. Appl. Sci.-Basel 11:4588. https://doi.org/10.3390/app11104588

Alonso, S., P. Dominguez-Salas, and D. Grace. 2019. The role of livestock products for nutrition in the first 1,000 days. Animal Frontiers 9:24–31. https://doi.org/10.1093/af/vfz033

Bailey, H. M., J. K. Mathai, E. P. Berg, and H. H. Stein. 2020. Pork products have digestible indispensable amino acid scores (DIAAS) that are greater than 100 when determined in pigs, but processing does not always increase DIAAS. J. Nutr. 150:475–482. https://doi.org/10.1093/jn/nxz284

Becker, T. 2002. Defining meat quality. In: J. P. Kerry, J. F. Kerry, and D. Ledward, editors, Meat processing: Improving quality. Woodhead Publishing Limited, Boca Raton, FL. pp. 3–23.

Beal, T., and F. Ortenzi. 2022. Priority micronutrient density in foods. Frontiers in Nutrition 9:806566. https://doi.org/10.3389/fnut.2023.1195752

Brewer, M. S., and F. K. McKeith. 1999. Consumer-rated quality characteristics as related to purchase intent of fresh pork. J. Food Sci. 64:171–174. https://doi.org/10.1111/j.1365-2621.1999.tb09885.x

Capper, J. L., and D. J. Hayes. 2012. The environmental and economic impact of removing growth-enhancing technologies from US beef production. J. Anim. Sci. 90:3527–3537. https://doi.org/10.2527/jas.2011-4870

Carrazco, A. 2021. How can cattle feed additives reduce greenhouse gas emissions? CLEAR Center at UC Davis. https://clear.ucdavis.edu/explainers/how-can-cattle-feed-additives-reduce-greenhouse-gas-emissions. (Accessed 27 May 2023.)

Channon, H. A, A. M. Payne, and R. D. Warner. 2002. Comparison of CO2 stunning with manual electrical stunning (50 Hz) of pigs on carcass and meat quality. Meat Sci. 60:63–68. https://doi.org/10.1016/S0309-1740(01)00107-3

Cook, H., and L. Schulz. 2022. The United States pork industry 2021: Current structure and economic importance. National Pork Producers Council. https://nppc.org/wp-content/uploads/2022/07/2021-NPPC-Economic-Contribution-Report-FINAL.pdf

EPA (Environmental Protection Agency). 2021. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2021-Main Report. 47, 124. https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf

FAO (Food and Agriculture Organization of the United Nations). 2023. Methane emissions in livestock and rice systems: Sources, quantification, mitigation and metrics. Rome. https://doi.org/10.4060/cc7607en

Foraker, B. A., B. J. Johnson, R. J. Rathmann, J. F. Legako, J. C. Brooks, M. F. Miller, and D. R. Woerner. 2022. Expression of beef- versus dairy-type in crossbred beef × dairy cattle does not impact shape, eating quality, or color of strip loin steaks. Meat Muscle Biol. 6:13926, 1–19. https://doi.org/10.22175/mmb.13926

Gonzalez, J. M. 2020. Poultry and pork muscle defects and meat quality—Consequences, causes, and management. J. Anim. Sci. 98:263. https://doi.org/10.1093/jas/skaa263

Hamilton, D. N., K. D. Miller, M. Ellis, F. K. McKeith, and E. R. Wilson. 2003. Relationships between longissimus glycolytic potential and swine growth performance, carcass traits, and pork quality, J. Anim. Sci. 81:2206–2212. https://doi.org/10.2527/2003.8192206x

Headey, D., K. Hirvonen, and J. Hoddinott. 2018. Animal sourced foods and child stunting. Am. J. Agr. Econ. 100:1302–1319. https://doi.org/10.1093/ajae/aay053

Honikel, K. O. 2009. Oxidative changes and their control in meat and meat products. In: F. Toldrá, editor, Safety of meat and processed meat. Springer, New York, NY. pp. 313–340. https://doi.org/10.1007/978-0-387-89026-5_12

Hosomi, R., M. Yoshida, and K. Fukunaga. 2012. Seafood consumption and components for health. Global Journal of Health Science 4:72–86. https://doi.org/10.5539/gjhs.v4n3p72

Huang, X., and D. U. Ahn. 2018. The incidence of muscle abnormalities in broiler breast meat—A review. Korean Journal of Food Science of Animal Resources 38:835–850. https://doi.org/10.5851/kosfa.2018.e2

Johnson, B. J., F. R. Ribeiro, and J. L. Beckett. 2013. Application of growth technologies in enhancing food security and sustainability. Animal Frontiers 3:8–13. https://doi.org/10.2527/af.2013-0018

King, D. A., M. C. Hunt, S. Barbut, J. R. Claus, D. P. Cornforth, P. Joseph, Y. H. Kim, G. Lindahl, R. A. Mancini, M. N. Nair, K. J. Merok, A. Milkowski, A. Mohan, F. Pohlman, R. Ramanathan, C. R. Raines, M. Seyfert, O. Sørheim, S. P.

Suman, and M. Weber. 2023. American Meat Science Association guidelines for meat color measurement. Meat Muscle Biol. 6:12473, 1–81. https://doi.org/10.22175/mmb.12473

Krebs, N. F., M. Mazariegos, A. Tshefu, C. Bose, N. Sami., E. Chomb, W. Carlo, N. Goco, M. Kindem, L. L. Wright, and K. M. Hambidge. 2011. Meat consumption is associated with less stunting among toddlers in four diverse low-income settings. Food Nutr. Bull. 32:185–191. https://doi.org/10.1177/156482651103200301

Krehbiel, C. R. 2017. Funding sources and challenges for animal science/ruminant nutrition research in the land-grant system. Plains Nutrition Council, 25.

Kuttappan, V. A., B. M. Hargis, and C. M. Owens. 2016. White striping and woody breast myopathies in the modern poultry industry: A review. Poultry Sci. 95:2724–2733. https://doi.org/10.3382/ps/pew216

Leroy, F., N. W. Smith, A. T. Adesogan, T. Beal, L. Iannotti, P. J. Moughan, and N. Mann. 2023. The role of meat in the human diet: Evolutionary aspects and nutritional value. Animal Frontiers 13:11–18. https://doi.org/10.1093/af/vfac093

Marti, D. L., R. J. Johnson, and K. H. Mathews, Jr. 2012. Where's the (not) meat? Byproducts from beef and pork production. Journal of Current Issues in Globalization 5:397–423.

Marušić, N., M. C. Aristoy, and F. Toldrá. 2013. Nutritional pork meat compounds as affected by ham dry-curing. Meat Sci. 93:53–60. https://doi.org/10.1016/j.meatsci.2012.07.014

McClelland, K. M., G. Rentfrow, G. L. Cromwell, M. D. Lindemann, and M. J. Azain. 2012. Effects of corn distillers dried grains with solubles on quality traits of pork. J. Anim. Sci. 90:4148–4156. https://doi.org/10.2527/jas.2011-4779

McWhorter, T. M., J. L. Hutchison, H. D. Norman, J. B. Cole, G. C. Fok, D. A. L. Lourenco, and P. M. VanRaden. 2020. Investigating conception rate for beef service sires bred to dairy cows and heifers. J. Dairy Sci. 103:10374–10382. https://doi.org/10.3168/jds.2020-18399

Miller, L. R. 2002. Reflection on the history, coordination, and funding trends for U.S. public meat research: Information to enhance resource allocation. J. Anim. Sci. 80:2085–2090.

Miller, R. 2020. Drivers of consumer liking for beef, pork, and lamb: A review. Foods 9:428. https://doi.org/10.3390/foods9040428

Modrow, K. M., and W. N. Osburn. 2020. Nitric oxide production in post-rigor pork semimembranosus muscle [abstract 38]. 2020 International Congress of Meat Science and Technology and 73rd AMSA Reciprocal Meat Conference, Virtual Meeting 2–7 August. Meat Muscle Biol. 5:27–28. https://doi.org/10.22175/mmb.11683

Morell, P., and S. Fiszman. 2017. Revisiting the role of protein-induced satiation and satiety. Food Hydrocolloid. 68:199–210. https://doi.org/10.1016/j.foodhyd.2016.08.003

Nagaraja, T. 2023. Beef-on-dairy and liver abscesses: What do we know? Florida Ruminant Nutrition Symposia. Gainesville, FL, 20–22 Feb. pp. 48–66.

NAMI (North American Meat Institute). 2020. 2019 Economic impact of the meat and poultry industry. Prepared by John Dunham & Associates. https://nami.guerrillaeconomics.net/res/Methodology.pdf

NCBA (National Cattlemen's Beef Association). 2022. National Beef Quality Audit [2022 executive summary]. https://www.bqa.org/Media/BQA/Docs/143783_nbqa_executive-summary-2022_prf_low-res.pdf. (Accessed 12 October 2023).

NCBA (National Cattlemen's Beef Association). 2023. Industry statistics. https://www.ncba.org/producers/industry-statistics. (Accessed 20 November 2023).

OECD-FAO. 2023. OECD-FAO Agricultural Outlook (Edition 2022). OECD Agriculture Statistics [database]. https://doi.org/10.1787/13d66b76-en. (Accessed 3 December 2023).

OECD-FAO. 2021. OECD-FAO Agricultural Outlook 2021–2030. pp. 163–177. https://www.fao.org/3/cb5332en/Meat.pdf. (Accessed 11 July 2023).

Oklahoma State University. 2023. Meating the workforce demand: FAPC launches Meat Mastery Program. https://news.okstate.edu/articles/agriculture/2023/meat-mastery-fapc.html. (Accessed 27 May 2024).

O'Quinn, T. G., D. R. Woerner, T. E. Engle, P. L. Chapman, J. F. Legako, J. C. Brooks, K. E. Belk, and J. D. Tatum. 2016. Identifying consumer preferences for specific beef flavor characteristics in relation to cattle production and postmortem processing parameters. Meat Sci. 112:90–102. https://doi.org/10.1016/j.meatsci.2015.11.001

Pinckaers, P. J. M., D. J. Domić, H. L. Petrick, A. M. Holwerda, J. T., F. K. Hendriks, L. H. P. Houben, J. P. B. Goessens, J. M. X. van Kranenburg, J. M. Senden, L. C. de Groot, L. B. Verdijk, T. Snijders, and L. J. C. van Loon. 2023. Higher muscle protein synthesis rates following ingestion of an omnivorous meal compared with an isocaloric and isonitrogenous vegan meal in healthy, older adults [online ahead of print]. J. Nutr. https://doi.org/10.1016/j.tjnut.2023.11.004

Polkinghorne, R., J. Philpott, H. Cuthbertson, and E. Wilcock. 2022. Meat science toward 2030: An international forum for the development of strategic objectives. Australian Meat Processor Corporation. https://www.ampc.com.au/getmedia/c7197619-ac4e-4b6a-9f06-a129d81af91d/220221-FINAL_REPORT_2017_1144_Meat-Science-Toward-2030.pdf?ext=.pdf

Polkinghorne, R., M. Koohmaraie, C. Kaster, T. Declan, and A. Rosati. 2023. Challenges and opportunities for defining the role and value of meat for our global society and economy. Animal Frontiers 13:75–81. https://doi.org/10.1093/af/vfad002

Pophiwa, P., E. C. Webb, and L. Frylinck. 2020. A review of factors affecting goat meat quality and mitigating strategies. Small Ruminant Res. 183:106035. https://doi.org/10.1016/j.smallrumres.2019.106035

Pork Checkoff. 2023. Enhancing quality and consistency: Insights from the National Retail Benchmarking Study. Published June 23, 2023. https://porkcheckoff.org/news/enhancing-quality-and-consistency/. (Accessed March 14, 2023).

Posthuma, J. A., F. D. Rasmussen, and G. A. Sullivan. 2018. Effects of nitrite source, reducing compounds, and holding time on cured color development in a cured meat model system. LWT-Food Sci. Technol. 95:47–50. https://doi.org/10.1016/j.lwt.2018.04.040

Ramanathan, R., L. H. Lambert, M. N. Nair, B. Morgan, R. Feuz, G. Mafi, and M. Pfeiffer. 2022. Economic loss, amount of beef discarded, natural resources wastage, and environmental impact due to beef discoloration. Meat Muscle Biol. 6:13218, 1–8. https://doi.org/10.22175/mmb.13218

Ramanathan, R., and R. A. Mancini. 2018. Role of mitochondria in beef color: A review. Meat Muscle Biol. 2:309–320. https://doi.org/10.22175/mmb2018.05.0013

Reinhardt, C. D., and M. E. Hubber. 2015. Control of liver abscesses in feedlot cattle: A review. Contribution no. 10-205-J from the Kansas Agric. Exp. Stn., Manhattan 66506. The Professional Animal Scientist 31:101–108. https://doi.org/10.15232/pas.2014-01364

Research and Markets. 2024. Meat, Poultry and Seafood Global Market Report. https://www.researchandmarkets.com/reports/5781136/meat-poultry-seafood-global-market-report?utm_source=GNE&utm_medium=PressRelease&utm_code=3m4gxw&utm_campaign=1854139+-+Meat%2c+Poultry+And+Seafood+Global+Market+Report+2023%3a+Advent+of+3D+Imaging+Systems+in+Poultry+Processing+Presents+Opportunities&utm_exec=como322prd. (Accessed 22 January 2024).

Schrobback, P., A. Zhang, B. Loechel, K. Ricketts, A. Ingham. 2023. Food credence attributes: A conceptual framework of supply chain stakeholders, their motives, and mechanisms to address information asymmetry. Foods 12:538. https://doi.org/10.3390/foods12030538

Seman, D. L., D. D. Boler, C. Carr, M. E. Dikeman, C. M. Owens, J. T. Keeton, T. Pringle, J. J. Sindelar, D. R. Woerner, A. S. de Mello, and T. H. Powell. 2018. Meat science lexicon. Meat Muscle Biol. 2. https://doi.org/10.22175/mmb2017.12.0059

Shahbandeh, M. 2022. Meat industry value worldwide in 2021 and forecast for 2022 and 2027. Statista. https://www.statista.com/statistics/502286/global-meat-and-seafood-market-value/. (Accessed 12 October 2023).

Shirsath, A. P., and M. M. Henchion. 2021. Bovine and ovine meat co-products valorisation opportunities: A systematic literature review. Trends Food Sci. Tech. 118:57–70. https://doi.org/10.1016/j.tifs.2021.08.015

Siddiqui F., R. A. Salam, Z. S. Lassi, and J. K. Das. 2020. The intertwined relationship between malnutrition and poverty. Frontiers in Public Health 28:8:453. https://doi:10.3389/fpubh.2020.00453

Smith, N. W., A. J. Fletcher, J. P. Hill, and W. C. McNabb. 2022. Modeling the contribution of meat to global nutrient availability. Frontiers in Nutrition 9:766796. https://doi:10.3389/fnut.2022.766796

Smith, Z. K., and B. J. Johnson. 2020. Mechanisms of steroidal implants to improve beef cattle growth: A review. J. Appl. Anim. Res. 48:133–141. https://doi.org/10.1080/09712119.2020.1751642

Swan, J. E., and J. A. Boles. 2002. Processing characteristics of beef roast made from high and normal pH bull inside rounds. Meat Sci. 62:399–403. https://doi.org/10.1016/s0309-1740(02)00028-1

Tonsor, G. T., and J. L. Lusk. 2022. U.S. perspective: Meat demand outdoes meat avoidance. Meat Sci. 190:108843. https://doi.org/10.1016/j.meatsci.2022.108843

University of Nebraska. 2023. NCTA, UNL collaborate with industry to boost training for meat processing sector. https://ncta.unl.edu/news-releases/ncta-unl-collaborate-industry-boost-training-meat-processing-sector. (Accessed 27 May 2024).

U.S. Meat Export Federation. 2022. Export statistics. https://www.usmef.org/export-data/export-statistics. (Accessed 8 September 2023).

U.S. Poultry and Egg Association. 2022. 2022 Poultry and egg economic impact study. https://poultry.guerrillaeconomics.net/res/Methodology.pdf (Accessed 04 October 2023).

USDA (U.S. Department of Agriculture). 2022. USDA NIFA invests $25M in meat and poultry agriculture workforce training. https://www.nifa.usda.gov/about-nifa/press-releases/usda-nifa-invests-25m-meat-poultry-agriculture-workforce-training. (Published May 24, 2022; Accessed 23 October 2023).

USDA. 2023. USDA agricultural projections to 2032. https://www.usda.gov/sites/default/files/documents/USDA-Agricultural-Projections-to-2032.pdf. (Accessed 24 July 2023).

USDA Economic Research Service. 2021. Meat and poultry plants employed about a third of U.S. food and beverage manufacturing employees in 2021. https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58286. (Updated 26 January 2023; Accessed 23 October 2023).

USDA Economic Research Service. 2022. Agricultural and food research and development expenditures in the United States. https://www.ers.usda.gov/data-products/agricultural-and-food-research-and-development-expenditures-in-the-united-states/. (Accessed 11 July 2023).

Ag and Food Statistics Charting the Essentials. 2023. Ag and Food Statistics Charting the Essentials. February 2023. Page 18. https://www.ers.usda.gov/webdocs/publications/105882/ap-111.pdf?v=3009.9. (Updated 22 February 2023; Accessed 12 February 2024).

USDA NIFA (National Institute of Food and Agriculture). 2023. Request for Applications: Agriculture and Food Research Initiative Competitive Grants Program Foundational and Applied Science Program. https://www.nifa.usda.gov/sites/default/files/2023-07/FY23-AFRI-FAS-RFA-MOD2.pdf

USDA NIFA. 2024a. National needs graduate and postgraduate fellowship grants program funding opportunity. https://cwww.nifa.usda.gov/grants/funding-opportunities/national-needs-graduate-postgraduate-fellowship-grants-program-funding-opportunity. (Accessed 27 May 2024).

USDA NIFA. 2024b. NIFA Grant Funding Dashboard. https://www.nifa.usda.gov/data/nifa-dashboards/grant-funding-dashboard. (Accessed 12 October 2023).

USDA NIFA, 2024c. The Agriculture and Food Research Initiative (AFRI) is the nation's leading competitive grants program for agricultural sciences. https://www.nifa.usda.gov/grants/programs/agriculture-food-research-initiative-afri

Workman, A. M., M. P. Heaton, B. L. Vander Ley, D. A. Webster, L. Sherry, J. R. Bostrom, S. Larson, T. S. Kalbfleisch, G. P. Harhay, E. E. Jobman, D. F. Carlson, and T. S. Sonstegard. 2023. First gene-edited calf with reduced susceptibility to a major viral pathogen. PNAS Nexus 2:pgad125. https://doi.org/10.1093/pnasnexus/pgad125

Wu, F., K. R. Vierck, J. M. DeRouchey, T. G. O'Quinn, M. D. Tokach, R. D. Goodband, S. S. Dritz, and J. C. Woodworth. 2017. A review of heavy weight market pigs: Status of knowledge and future needs assessment. Translational Animal Science 1:1–15. https://doi.org/10.2527/tas2016.0004

Zaharia, S., S. Ghosh, R. Shrestha, S. Manohar, A. L. Thorne-Lyman, B. Bashaasha, N. Kabunga, S. Gurung, G. Nambirebe, K. H. Appel, L. Liang, and P. Webb. 2021. Sustained intake of animal-sourced foods is associated with less stunting in young children. Nature Food 2:246–54. https://doi.org/10.1038/s43016-021-00259-z

Zhang, X., K. Virellia To, T. R. Jarvis, Y. L. Campbell, J. D. Hendrix, S. P. Suman, S. Li, D. S. Antonelo, W. Zhai, J. Chen, H. Zhu, and W. Schilling. 2021. Broiler genetics influences proteome profiles of normal and woody breast muscle. Poultry Sci. 100:100994. https://doi.org/10.1016/j.psj.2021.01.017