DOI: https://doi.org/10.21323/2414-438X-2021-6-4-335-342

Available online at https://www.meatjournal.ru/jour
Original scientific article
Open Access

Received 14.10.2021
Accepted in revised 14.11.2021
Accepted for publication 24.11.2021

MEAT CONSUMPTION: THEORY, PRACTICE AND FUTURE PROSPECTS

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Keywords: *authenticity, modern meat market, nitrate, meat replacement, non-thermal processing, nutritive value, consumer preference*

Abstract
This research reviewed human meat consumption and highlighted associated history, challenges and benefits. Selected literature for the manuscript was from relevant titles and reliable international sources. From early times of the mankind meat consumption and animal husbandry were inseparable parts of living, and with similar consequences as dramatic influence on environment. Human need for meat consumption fueled development of large world markets with incredible trade, processing and consumption. This overconsumption has caused health problems associated with high intake of cholesterol and sodium chloride. Another problem with meat consumption is the use of additives in processed products. In modern time these problems are tackled by the use of additives from plants that have health benefits. Thermal processing is yet another problem with meat consumption that food industry and science addresses by non-thermal replacements (e. g. high-pressure processing and electrotechnologies). Recently, interesting alternatives for meat processing included 3D Printing that is able to engineer admirable meat products from by-products. However, this technology might need to employ enzymes such as transglutaminase, associated with potential health problems and misleading the customers. Unfortunately, fraudulent activities are common for meat products and it would be prudent to organize enforcement centers with at least police and analysts skilled in chemometrics and various laboratory techniques for food defense. It seems as humankind expands it will seek more proteins from plant, insects, unicellular biomass, and synthetic meat than from the animal origin, however all of the alternatives must be carefully evaluated against consumer acceptance, public health and environmental concerns.

For citation: Putnik, P., Kovačević Bursać, D (2021). Meat consumption: theory, practice and future prospects. *Theory and practice of meat processing,* 6(4), 335-342. https://doi.org/10.21323/2414-438X–2021-6-4-335-342

Introduction

Human cravings for animal meat probably dates back to the origins of humankind [1]. The earliest archeological evidence of early humans includes common stone tools as well as animal remains. The earliest human cave art, dating back 44,000 years ago, depicts scenes of hunting native animals [2]. Even in human physiology, there are specific metabolic pathways, such as for iron metabolism, to better utilize nutrients from animal meat [3]. For instance, the transport of dietary iron in the human body occurs through two pathways, one for non-heme iron and one for the heme-iron. Needless to say, that the historically hemoglobin in the human diet is mostly of animal origin or derived from meat.

Objects and methods

The subject of the study was to provide an overview of human meat consumption and highlight the challenges and benefits associated with it. The focus was on a brief anthropological and historical review, reasons for the popularity of meat and its nutritional value, describing modern production and processing, providing current trends in meat science, and finally projections of future trends related to meat production, processing, and consumption. The literature review included the electronic databases Web of Science, PubMed, Scopus, ScienceDirect, and Google. References were selected for the manuscript whose titles and descriptions were relevant to the topic and were from reliable international sources.

Development of International Meat Market

The human population grew, so did the need for reliable meat production. As hunting proved to be an inadequate source of meat, a new branch of agronomy, animal husbandry, emerged [4]. The earliest domesticated animals included sheep, goats, pigs, cows and chickens, probably more than 10,000 years ago [4]. Since ancient civilizations, the Egyptians, Romans etc., the breeding of animals for meat increased as the human population grew [4, 5]. However, with the decline of the Romans in Middle Ages, the systematic breeding of animals for meat declined until Agricultural Revolution in Britain around the 18th century. What was new here was the selective breeding of animals, which improved the production of meat and paved the way for modern meat production [6].

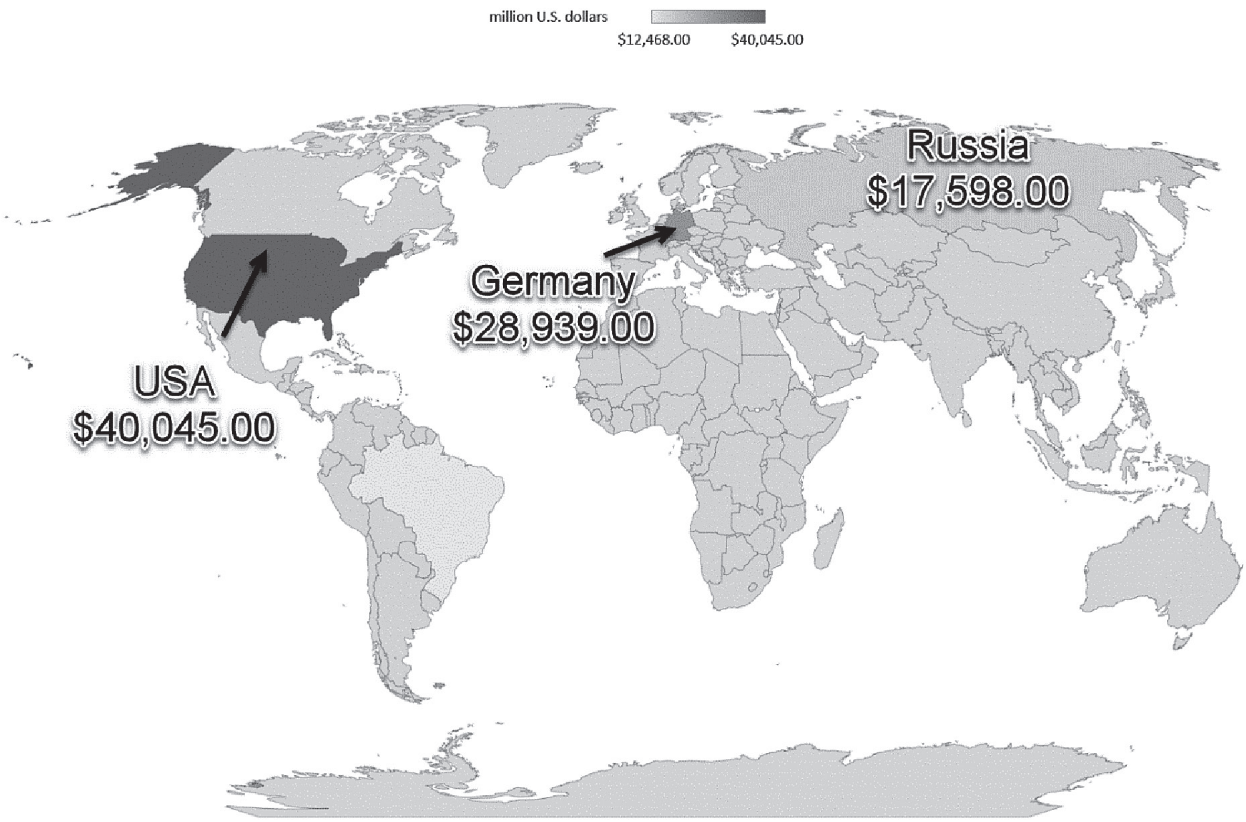

Figure 1. Top 3 worldwide revenues from meat products and sausages in 2021 (in millions of U.S. dollars) [7]

The value of modern meat market was $838 billion in 2020, and it is expected to increase to $1 trillion by 2025. In 2020, 328 million tons of meat were produced worldwide, equivalent to an annual per capita consumption of 35 kilograms of meat. The largest meat markets in the world (Figure 1.) are the US, Germany, Russia, France and Brazil [7]. The US is the largest meat producer and exporter in the world, especially for beef. Currently, most meat is produced in Asia (136 million tons), with pork and poultry being the most produced, while lamb is the least produced. The largest companies producing meat are Tyson, Hormel Foods, and National Beef [7]. It is hard to believe but in 2014 alone, humanity consumed 1.47 billion pigs, 545 million sheep, 444 million goats and 300 million cattle [8]. By 2021, that number will be 1 billion cattle, 0.75 billion pigs, and 0.1 billion chickens [9]. All of the data presented shows the sheer magnitude of modern meat production. However, even though modern meat production is one of the largest industrial sectors in the world, there are still many meat production challenges that need to be addressed.

Environmental concerns

As in prehistory, the main problem with meat consumption is the growing human population, as livestock requires more land, which in turn suffers from desertification [10]. Even more, over 65% of infectious diseases are transmitted to humans through livestock production, in an area that covers 70% of the total arable land mass [10]. In 2017, Stockholm International Water Institute stated that 70% of water is used for agriculture [11], with animal farming consuming most of it [10]. Additionally, global food systems are responsible for 30% of all greenhouse gas emissions produced, with 60% of that coming from animal agriculture [12].

Nutritive value and importance of meat

The need for meat consumption has always been a strain on natural resources, from prehistoric times until today, as extinctions of entire species (e. g. Mammoths) have been linked to human expansion on the planet after the period of the Ice Age [13,14]. The changes affecting the environment have now taken different forms, but the effects are similar to those experienced thousands of years ago. Unsurprisingly, modern meat production has faced problems that include sociocultural issues, negative impacts on human health (e. g. the introduction of antibiotics into the environment during animal farming, which can create new strains of pathogenic bacteria that are resistant to antibiotics), deforestation of land, pollution of water, global warming and so on [11]. So what drives people to consume meat at these costs throughout the history?

In the past, animals were hunted to consume their fat to increase the chances of survival during the cold seasons. Some carnivorous species have continued this behavior today, such as polar bears, which eat mainly fats from seals to build-up energy reserves for the harsh winter time. Researchers suggest that this type of diet may have played an important role in the evolution of humans as a whole [15]. Furthermore, meat is known to be an excellent source of proteins, lipids, minerals and vitamins that humans need to survive [16]. On average, an adult human requires 50–80 g of protein per day with all essential amino acids [17].

Albeit protein content may vary depending on the type of carcasses, it is generally similar among different mammals, birds, and fish [16]. Undeniably, meat is an important source of protein, Fe, Zn, Se, and vitamins D and B12 for many people [18]. However, in order to get nutrients from meat, it is important to process it, because even simple cooking over fire greatly increases the amount of nutrients available compared to raw alternatives. Thus, the discovery of fire and cooking allowed the human body access to more energy, and thus running more powerful brain that allowed our species to become the dominant on the planet [19]. Cooking with fire was the earliest form of thermal processing of meat, which along with drying, ensured the survival of early humans and was used into modern times.

Production and Processing

Apart from the environmental problems, there are also problems with meat production in terms of production and processing. According to the World Health Organisation (WHO), some meat products are classified as Group 1 carcinogens, due to the use of nitrates, which are a common additive in meat processing [20]. Nitrates are added to meat as an important antioxidant that prevents the growth of anaerobic bacteria (e. g., *Clostridium botulinum*), lipid oxidation, and off-flavors while preserving the appealing color of the products [21]. On the other hand, nitrates also promote the production of N-nitrosamines, which have been associated with an increased risk of cancer [20]. In addition to nitrates, several groups of synthetic additives such as butylated hydroxytoluene, butylated hydroxyanisole, tertiary butylhydroquinone, and propyl gallate, which are used to inhibit microbial growth and oxidation of meat [22], have negative health effects because they pose a cancer risk [23].

Current efforts in meat science are primarily concerned with the replacement of additives with natural alternatives and the use of non-thermal processes. This mainly involves the aforementioned nitrate salts, which are replaced by natural additives (antioxidants) from aromatic plants and their oils, bioactive peptides from eggs [24] fish, milk and meat [25], nuts [26]; polyphenols from fruits such as berries [20,27], and others [28].

Another alternative to synthetic additives that can provide similar technological functions is probiotics, which function primarily as starter cultures. In addition to microbial inhibition, probiotics have the ability to regulate fermentation, shorten product ripening, and improve food preservation [29]. They are excellent raw materials for various (functional) foods and are generally considered safe for consumption. Nevertheless, their consumption may have adverse consequences for some consumer groups, as their use in the public diet is not sufficiently regulated by law, which is certainly a concern due to the potential lack of consumer safety when consuming such products [30,31]. Advantages and disadvantages can be enumerated in all these approaches, as no approach is perfect. Nevertheless, positive changes can be expected in the future, which can already be observed on grocery shop shelves. We are seeing an increasing number of foods (and meat products) that contain natural additives that are less harmful and even helpful to health (e. g., they contain functional components such as plant polyphenols).

Another, more dietary problem with meat consumption is the ingestion of cholesterol. This infamous molecule, similar to unsaturated lipids is susceptible to oxidation [32], and tends to agglomerate on the walls of blood vessels, which can lead to blood flow blockage and consequent cardiovascular problems [33,34]. Besides cholesterol, processed meat contains larger amounts of salt (NaCl), which in large amounts increases blood pressure. In addition, meat is naturally rich in carnitine, which when broken down by human physiology, increases the risk of atherosclerosis by generating trimethyl amine N-oxide [18].

Replacing fattening calories and cholesterol from meat is a somewhat complicated task to accomplish. For this purpose, industry and academia use gels and emulsions made from marine organisms or plants [35–38]. Here, researchers are concerned with finding the best alternative that increases the nutritional value of a product (reducing saturated fats) while maintaining all the benefits of naturally occurring fats from meat, namely sensory value, texture, technological properties, etc. [39]. As with the replacement of synthetic antioxidants, fat substitutes also have various (dis)advantages that science and industry are meticulously trying to document in order to meet consumers demands, health requirements, regulatory requirements and market value of the products.

Even the simple thermal processing and smoking of meat has a similar result, where the heat generates the production of toxic N-nitrosamines in addition to polycyclic aromatic hydrocarbons [20]. Needless to say, meat oxidation is a major problem for both consumers and industry, as it negatively affects health and lowers the economic profitability of production [32]. It has been documented that oxidized products in meat (e. g., carbonylated proteins) are associated with several diseases as cancer, Alzheimer's disease, chronic renal failure, and diabetes [20].

In order to reduce the thermal exposure and the amounts of additives in meat (and food in general), food scientists have turned to the use of non-thermal technologies that are able to provide the obligatory inactivation of microorganisms while preserving nutritional value of the meat. Thermal processing, such as grilling, produces harmful carcinogenic compounds and an appealing, juicy flavor that is appreciated by many. Grilling is one of the most common cooking methods for meat, and the taste is achieved by denaturing the meat on the surface, creating the familiar crunchy coating [40]. It is also probably the oldest cooking method as it was used in prehistoric times. The main reasons for thermal processing are enzymatic and microbial inactivation to extend the shelf-life of meat

[41], and improvements in digestibility of nutrients. Other ways of preparing meat include boiling, blanching, microwaving, oven cooking, and roasting, each of which has its own advantages and disadvantages.

An alternative to conventional cooking is the *sous-vide* method, which is preferred by many restaurant professionals [42], because it better preserves the taste and natural characteristics (juiciness) of the meat for their customers [43]. This technology involves the use of plastic bags used in *sous-vide* equipment to hold vacuumed meat that is systematically subjected to a very slow cooking process (up to 48 hours) [44]. Initially, the meat can be semi-cooked or raw, depending on the occasion, and is then placed in water baths at 65–95 °C. In this way, ready-to-eat food of high quality and with low production costs can be produced. The meat obtained in this way retains its fresh quality [45,46].

Among the increasingly growing number of alternatives to conventional thermal meat processing, the most notable alternatives are non-thermal treatments such as high pressure based technologies, electrotechnologies, e. g. pulsed electric fields (PEF), or the use of ultrasound energy which alleviates many of the concerns associated with thermal treatments. High pressure processing (HPP) is one of the most successful advanced technologies for meat [47], accounting for 20–30% of all food processed with this technology. In 2019, 400,000 tons of meat were processed using this HPP, mainly in the United States. This technology offers minimal changes in nutritional and sensory quality and is suitable for various meats [47]. Testament to the potential of high pressure processing is the U. S. Food and Drug Administration (FDA) approval for use in industry for cold pasteurization [48].

As already known, in pulsed electric field technology, high-intensity electric fields (> 0.1 kV/cm) are applied to the meat between two electrodes for a very short time (in the range of milliseconds to microseconds) [49]. The most important phenomenon associated with PEF is the occurrence of electroporation, which increases the juiciness of the meat [50]. Another advantage is the minimal effect on the microstructure of the meat [50], while shortcomings include the strong dependence on intrinsic factors of the treated food/meat which may reduce its effectiveness [49].

Both of the above technologies treat meat at lower temperatures (even room temperature) while ensuring microbial safety and product quality [50]. However, sometimes these technologies are not able to inactivate microbes efficiently, and they are combined under the concept of 'Hurdle technology' that essentially encompasses combination(s) of different food preservation factors that synergistically ensure food protection and microbial inactivation [51].

Next comes ultrasound technology, which is useful for inactivating microorganisms, but is more commonly used as a mechanical aid in meat processing. This technology is based on acoustic energy, which provides a non-ionizing, non-invasive, and non-polluting form of mechanical energy [52]. It is suitable for tenderizing meat, inactivating microbes on the surface of poultry, and accelerating the cooking process [53]. Although this technology has significant potential for meat processing, it has not yet been massively used in production.

Another interesting advanced technology that is not designed to solve food safety issues is 3D printing [54]. This technology has the ability to utilize remnants of meat from processing which lacks aesthetics and market value, as an entirely new raw material for legitimate food products [54]. The greatest strength of this technology is the endless aesthetic possibilities for product design, limited only by the imagination, consistency, and texture of the material used in the device. Moreover, it is an additive technology in which a specific product is shaped by patiently making a single slice at a time [55]. Since this technology is capable of using virtually any type of paste-like material for food production, it can utilize various by-products of the food industry that are otherwise considered waste. Therefore, it is referred to as an environmentally friendly approach, however, in this case, food safety must be ensured by other means, such as hurdle technology. Recently this amazing technology allowed researchers to print the famous Wagyu beef which resembles the natural characteristics of the real steak [56].

Another enzyme associated with 3D printing of meat in this particular research is the controversial transglutaminase, also known as "meat glue." This enzyme enables the joining of different pieces of meat into a larger structure that looks like a normal slice of meat [57]. In 2010, the use of transglutaminase was banned in the EU due to concerns about labeling and potential to fraud the customers into believing they were buying a usual piece of meat. Transglutaminase is able to catalyze the binding of acyl transfer between the γ-carboxyamide side of the peptide chain and primary amines. As a consequence, the linked peptides form larger polymers with high molecular weight, thus altering the structural properties of food [58]. Although this enzyme has the potential to reduce the amounts of by-products from production, it has also been linked to health problems, namely autoimmune diseases, intestinal permeability, celiac disease, Alzheimer's disease and Huntington's disease [57].

Legal issues

Given the high demand in meat markets, it is not surprising that numerous offenders tend to adulterate meat products [59]. Unfortunately, meat adulteration is a widespread problem with numerous incidents, material losses, and dire consequences for human health [60,61]. Terminologically, food crimes of any kind are activities that focus on the mistreatment of consumers by various groups or individuals with clear (criminal) motives and intentions [62,63]. One of the first reported cases of food fraud involved the replacement of beef with horsemeat and pork, which led to legislative changes in the EU and Germany [64]. This scandal revealed weaknesses in public food control, traceability and origin of food in a supply chain, while adulteration of meat products (and others) remains a serious problem even today. Detailed explanations of the problem of authenticity have been published elsewhere [65].

The problems with the aforementioned food frauds related to meat can be addressed in various ways, but mainly through increased legal controls, governmental monitoring of food markets enforced with the police and other representatives of the state monitoring system, the establishing legal framework for the most affected fraudulent activities that are not yet in place, the introduction of food protection systems along the entire food chain, and vigilant control of raw materials and their traceability [66]. This should include the establishment of centers with analytical support and techniques capable of quickly detecting tempering of products and working closely with the police [60,67,68]. In addition to "wet" laboratory techniques, such centers should have data analysts skilled in chemometrics and management of large datasets, as fingerprinting of food commodities in most cases relies on myriad data points to draw useful conclusions that are difficult to extract unless managed by experienced professionals [69]. Among the most useful chemometric techniques are multivariate analyses such as factor analysis, different data clusters, mathematical modeling, multivariate analysis of variance etc. [70,71].

Meat replacements and alternative protein sources

Clearly, the habitable space on the planet is shrinking due to the ever-increasing human population and animal agriculture. Therefore, humans must either figure out how to use the uninhabitable parts of the world or opt for food solutions that are more compatible with environmental constraints. Among the most likely solutions already available are alternative sources of protein that do not come from farming livestock. In first place are proteins from single-celled organisms (e. g. bacteria or yeasts), followed by marine organisms (algae seaweed), insects and plants [17].

Bacteria have the highest protein content in the biomass (50–80%), followed by yeasts (30–75%) and molds (20–45%). Most of the unicellular biomasses contain abundant lysine but lack methionine and cysteine. However, the addition of methionine makes this biomass equivalent to animal proteins [72]. In addition, this biomass is a good dietary source of vitamin B and minerals, while yeasts also have a useful probiotic effects [17]. On the other hand, the main disadvantage of unicellular biomass is the high content of nucleic acids, which can lead to gout if consumed in excess of 30 g/day. Seaweed and algae are protein alternatives that do not pollute the environment, and also provide good proteins, vitamins and minerals. Nevertheless, their use is not widely accepted in the industry due to the high cost of production and the development of products with appealing taste [73]. Some other organisms such as krill are a viable protein source, but their biomass contains chitin, which is an allergen [74]. Insects are another alternative (or supplement) to meat processing, with digestibility of their proteins comparable to egg proteins or meat [17]. Farming insects for protein requires less land area, has lower greenhouse gas emissions per unit of biomass than farming livestock, and requires fewer economic resources. Apart from human nutrition, insect biomass can also be used for fishmeal, which is also an agricultural approach that is less polluting than livestock farming [10]. Unfortunately, insects are not well accepted as part of the diet in Western countries because they are considered disgusting [73] and their biomass also contains chitin, which is considered an allergen [74].

Compared to meat proteins, plant-based counterparts are preferable because of their lower environmental impact. One of the most important sources of plant proteins are cereals (e. g. wheat and barley) and legumes (e. g. soy, beans, lupins and peas). Ecology aside, there are no ethical animal welfare issues involved in the production of plant proteins. However, there is another controversy associated with legumes, namely soy, and genetically modified organisms that are, for better or worse, poorly accepted by customers. Plant products do not naturally contain cholesterol, but other limitations include lower digestibility compared to meat and risk of celiac problems due to the presence of gluten [17]. In any case, plant proteins will be an indispensable part of the diet in the future and their share is only expected to increase.

In vitro "cultured" or "synthetic" meat is an interesting alternative for people who do not want to give in to their carnivores urges and become vegetarians, but can still be environmentally conscious and reduce their environmental footprint on the planet [75]. But is this really the case?

In vitro meat is essentially laboratory-grown tissue from muscle stem cells of an animal in fetal bovine serum (FBS) derived from bovine blood [75]. With cellular proliferation and interlinking final product looks like usual meat without fats and with sensory quality similar to real meat. Originally a very expensive process, this currently has the potential to be used in meat production on an industrial scale [75]. Opponents of this approach point out that there are a number of problems with this method of meat production. Firstly, the main problem is the use of FBS, as it supposedly has to come from dead calves. While this reduces ethical issues related to the protection of animal rights, still they remain unsolved as animals continue to be killed in the process but to a lesser extent [76]. An alternative is the use of plant-based serums, which are claimed to be a sufficient substitute. The next problem is the use of antibiotics, fungicides, and growth hormones that are necessary to prevent contamination and proliferation of *in vitro* cell lines. Yet another issues that needs to be addressed is the objective and quantifiable assessment of the environmental, health and legislative impacts of conventional and synthetic meat. Even though this approach has the potential to solve a number of problems related to meat consumption, there are also many (un)known caveats that need to be considered, especially now that this technology is still in its early stages of development. In other words, mass application in production should be carefully waged prior any rushing into actions that could be detrimental to public health and the general population.

Conclusion and Future trends

Humans always had preferences for meat consumption and this is unlikely to change in the future despite the fact that such preferences have negative repercussions on the environment. Testament to this is the enormous size of the current meat market and industrial production, which is expected to increase in the future. Meat provides high quality protein, vitamins and minerals while offering pleasure when consumed. The high level of interest in the trade of meat and its products has led (and may still lead) to fraudulent activities that have resulted in public health damages and economic losses for producers. Consequently, four actions are available to the food industry to address the above challenges, namely, improving the current regulatory framework to protect the authenticity of food, hiring more laboratory and data analysts, improving food production with healthier and less toxic additives, improving production to produce fewer undesirable compounds in meat products, and finding a meat substitute that meets all the benefits that meat provides for human nutrition while avoiding all the disadvantages of animal agriculture. Solutions to address the overconsumption of meat and the associated health risks also include nutritional education by public health officials and other key players in the food chain (e. g. government, consumer protection non-governmental organizations, industry, etc.).

It is expected that in the future proteins from insects and plants will account for a higher proportion of total dietary proteins in the market, but one problem that still needs to be solved is consumer acceptance due to imperfect taste. Social marketing campaigns may be helpful to improve the public image of “insect meat” and additional research may address this sensory acceptance problem. The innovative approach of growing meat in a petri dish is a possible solution that can theoretically solve most animal husbandry problems, but the current literature shows that there is still a long way to go from theory to practice. Finally, it remains to be seen how meat science and industry can satisfy the many conflicting sides of an individual who is clashed between a preference for eating meat and protecting the environment and is not a fan of slaughtering animals for consumption. This is indeed no easy task.

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The authors declare no conflict of interest.