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REVIEW ARTICLE

Comprehensive Review on Tackling Antibiotic Resistance in Traditional Meat via Innovative Alternative Meat Solutions

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A B S T R A C T

The use of antibiotics in industrial livestock farming has contributed to increased meat production, but it has also sparked significant concerns regarding food safety, public health, and environmental sustainability. Beyond public health and sustainability concerns, consumers also face direct exposure risks through antibiotic residues in meat. In contrast, excessive antibiotic use in livestock significantly contributes to the global rise of antibiotic resistance (ABR). The spread of antibiotic-resistant bacteria threatens clinical treatment effectiveness and poses a significant global health challenge. Additionally, ecological contamination from antibiotics in animal waste negatively impacts environmental microbial communities and facilitates resistance gene dissemination. Although regulatory actions have restricted antibiotic use and residues, enforcement remains inconsistent across countries, emphasizing the need for strategies to reduce antibiotic dependency in meat production. Second-generation meat technologies have emerged as promising alternatives. Plant-based meats, cultured (lab-grown) meats, and microbial protein products offer antibiotic-free protein sources that meet growing consumer demand while mitigating risks linked to conventional meat production. Legumes and grains are the primary sources of plant-based meat alternatives and are not treated with antibiotics in the same way as livestock. As a result, plant-based proteins generally present a significantly lower risk of antibiotic exposure, although indirect contamination cannot be entirely ruled out. Cultured meat does not use antibiotics, as it grows animal cells under sterile laboratory conditions, and replicates the meat experience closely, both in texture and taste. Through fermentation of tiny single-cell organisms, microbial proteins offer a renewable, scalable, and antibiotic-free source of protein. While regulatory measures exist, inconsistent enforcement and continued reliance on antibiotics in animal agriculture have intensified the global ABR crisis. Although alternative meat technologies such as plant-based, cultured, and microbial proteins have gained attention as sustainable and antibiotic-free protein sources, their role in reducing antibiotic dependency and mitigating ABR risks remains underexplored in current literature. This review addresses that gap by examining the health and environmental threats posed by antibiotic use in livestock, evaluating the antibiotic-free potential of meat alternatives, and assessing their contributions to sustainability, ABR mitigation, and global food security. It also outlines the challenges, limitations, and future directions for transitioning toward safer, more resilient protein systems.

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INTRODUCTION

Over the last three decades, global demand for meat and meat products has risen substantially due to increasing population levels, urbanization, and income (Hwang *et al*., 2025; Samad *et al*., 2025). To meet this growing demand, traditional livestock farming has become very intensive with the daily overuse of antibiotics for disease treatment, prevention, and growth promotion purposes (Manyi-Loh *et al*., 2018). Antibiotics have been highly effective in preventing and controlling animal diseases, increasing productivity, and improving the welfare of animals (Kasimanickam *et al*., 2025). On the other hand, their indiscriminate use constitutes a significant threat to food safety and the sustainability of healthy ecosystems (Iwu *et al*., 2020). The improper use of antibiotics in livestock production can lead to residues of the drug within meat and other animal-based food products, which could cause adverse effects on the human population in terms of allergic and toxic consequences (Arsène *et al*., 2022).

Excessive misuse of antibiotics in livestock production directly triggers the development and spread of ABR bacteria (Serwecińska, 2020). The resistant pathogens can infect humans by affecting the treatment protocols and present significant global health risks through the food chain (Sagar *et al*., 2023). To raise awareness of the severity of the concern, the World Health Organization (WHO) reported that ABR is among the top ten global health harms, and it underlines the need for global action to prevent this problem (World Health Organization, 2023).

The excess use of antibiotics is a concern from an animal health perspective and an environmental problem (Arsène *et al*., 2022). Antibiotics and their metabolites in animal manure enter soil and water systems (Muhammad *et al*., 2020). This alters microbial communities and promotes horizontal transfer of resistance genes (Xie *et al*., 2018). Such ecological pollution intensifies ABR control challenges while endangering species and the ecosystem. International regulations are limiting the use of antibiotics in agriculture and monitoring residue levels in meat products (Ghimpețeanu *et al*., 2022). Practical implementation remains difficult, particularly in developing nations, and often due to a lack of infrastructure and regulatory monitoring. Meanwhile, increasing consumer awareness and the safety of food have driven demand for antibiotic-free meat and pressured the meat industry to adopt more sustainable and safe production practices (Haque *et al*., 2020). In this scenario, alternative meat technologies have shown up as potential solutions to these multiple challenges. Meat alternatives are the food product that replicates sensory, nutritional, and functional properties of conventional meat but not from traditional animal sources (Ismail *et al*., 2020). Such alternatives comprise plant-based meat (Bakhsh *et al*., 2021; Samad *et al*., 2024a) substitutes, cultured (lab-grown) meat (Samad *et al*., 2024b), and microbial proteins through fermentation (Humpenöder *et al*., 2022). These innovations can partially cover global meat demand and are also able to minimize the risk of antibiotic resistance through meat consumption.

The protein content in most plant-based meat products is sourced from either legumes or grains, which are free from antibiotics and therefore do not have residues or resistant bacteria associated with them (Santo *et al*., 2020). Cultured meat is lab-grown meat obtained by culturing animal cells in enzymatic conditions, which gives it a relatively well-developed and high-strength alternative that mimics the texture and flavor of conventional meat (Alam *et al*., 2024). Other potential and sustainable alternative protein sources include microbial proteins, which are defined as the single-cell fermentation of bacteria, yeast, and algae that have no exposure to antibiotics and are thus a high-quality protein source (Hadi and Brightwell, 2021).

This review discusses the worldwide problems caused by traditional meat production through excessive use of antibiotics and considers alternative meat technologies as potential meat substitutes. This review sheds light on the effects of excessive use of antibiotics in meat production. Several studies have been done in the past 10 years on the use of antibiotics in meat production, which highlights the importance of this topic in the veterinary sector, while the keywords of those studies are shown in Fig. 1. Furthermore, this review discusses the classification of available alternative meat products, their potential benefits and drawbacks, and their role in reducing antibiotic resistance by promoting a sustainable protein supply for future generations.

Antibiotics in Meat: Antibiotic use in conventional meat production is a complex and controversial (Sofos, 2008). It affects food safety, public health, environmental sustainability, and regulatory policies (Serwecińska, 2020). While antibiotics have traditionally played a vital role in boosting livestock productivity and preventing disease, their overuse and misuse have raised serious societal concerns and led to adverse health and environmental impacts.

The most important sociological point of interest concerns antibiotic residues, especially in animal-based food (Ghimpețeanu *et al*., 2022). When the appropriate withdrawal period is not observed between treatment and slaughter, antibiotic residues can remain in the tissues of food-producing animals such as muscle, liver, and fat (Canton *et al*., 2021). The presence of maize and soybean residues in animal-based foods (milk, meat, eggs, etc.), resulting from the use of genetically modified (GM) crops, poses serious health risks to humans, including allergic reactions, toxicity, and disruption of gut microbiota (Bawa and Anilakumar, 2013). These issues are most acute among vulnerable populations, such as children and the elderly. This situation is alarming as long-term exposure to non-therapeutic amounts of antibiotic residues has chronic and health-related outcomes. Furthermore, common problems related to the use of antibiotics in livestock or poultry farming are discussed in the Table.1

Development of Antibiotic Resistance: The overuse and misuse of antibiotics in the animal sector is one of the main drivers of the development of ABR, a global health crisis (Salam *et al.,* 2023). Prophylactic use and the use as growth promoters of antibiotics apply selective pressure on microbial populations, allowing resistant strains to endure and multiply (Capita & Alonso-Calleja, 2013). Antibiotic-resistant organisms can grow in farm animals, contaminate meat, and survive slaughter, processing, and consumption (Monger *et al.,* 2021). Resistant bacteria can spread to humans through contaminated food or environmental pathways (Serwecińska, 2020). This can lead to harder-to-treat infections, prolonged illness, more extended hospital stays, higher healthcare costs, and increased mortality risk. The One Health approach addresses ABR through integrated action across human, animal, and environmental health. Its cross-sectoral and transdisciplinary nature reflects the complexity of antibiotic resistance as a global issue.

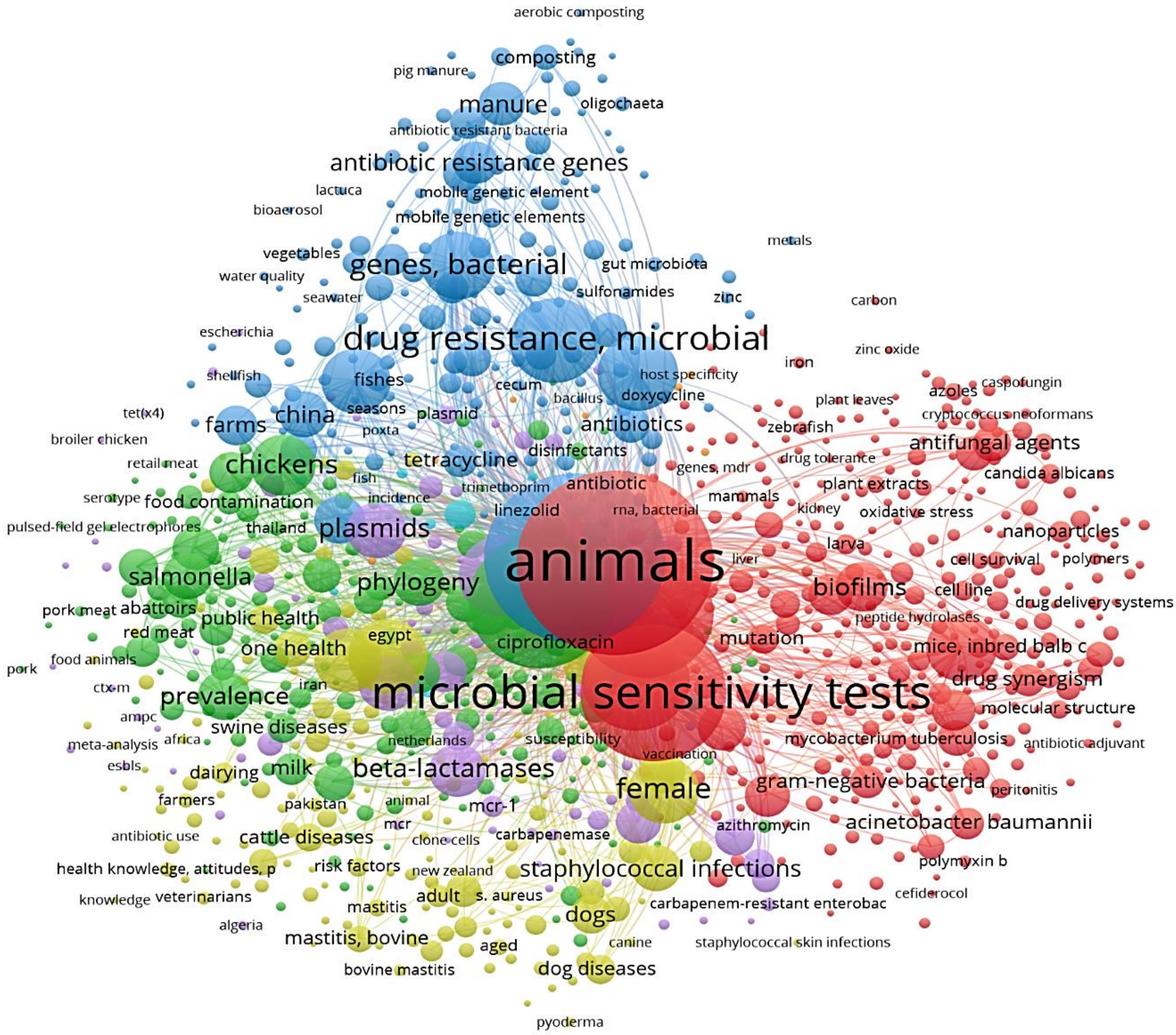

Fig.1: A keyword co-occurrence network, which is generated from literature published over the past ten years on antibiotic resistance due to animal production.

Table 1: Common Problems Associated with Antibiotics in Conventional Meat Production through livestock farming

Problem Area	Description	Implications	References
Antibiotic Residues in Meat	Presence of antibiotic traces in meat tissues due to insufficient withdrawal periods	Allergic reactions, toxicity, gut microbiome disruption	Arsène *et al*., 2022
Development of Antibiotic Resistance (AMR)	Overuse promotes resistant bacteria in animals and meat products	Harder-to-treat infections in humans, increased healthcare costs	Sagar *et al*., 2023
Environmental Contamination	Antibiotics released through animal waste contaminate soil and water	Disrupts microbial ecosystems and spreads resistance genes	Cycoń *et al*., 2019
Regulatory and Monitoring Gaps	Uneven enforcement and lack of infrastructure to monitor antibiotic use and residues	Continued misuse and ineffective control	Ghimpețeanu *et al*., 2022

Environmental Effects Besides the impact of antibiotics on food safety and human health, their usage in animal production also poses significant environmental risks. Antibiotics and their active metabolites are primarily excreted in animal waste, which is often applied to farmland or discharged into natural water bodies (Muhammad *et al.,* 2020). This leads to soil and water pollution and the disruption of native microbial communities responsible for nutrient cycling, which are critical for ecosystem function (Cycoń *et al.,* 2019). Additionally, antibiotic exposure in the environment can promote the acquisition and horizontal transfer of resistance genes from avirulent to pathogenic bacteria. This process increases the environmental spread of antibiotic resistance. The long-term existence of antibiotic substances in the environment preserves a reservoir of resistance (Larsson and Flach, 2022), making it more difficult for the world to reduce the spread of resistant infection.

Monitoring and Regulation: Many countries have regulatory frameworks to restrict animal antibiotic use for human consumption and set maximum residue limits (MRLs) in meat products (Ghimpețeanu *et al.,* 2022). However, enforcement of these regulations is often inconsistent or weak, especially in low- and middle-income countries. Contributing factors include the absence of systematic surveillance systems, under-resourced regulatory bodies, limited stakeholder awareness and compliance, and widespread malpractice. In certain regions, the availability of antibiotics over the counter facilitates their large-scale misuse (Endale *et al.,* 2023). Moreover, the increasing globalization of the meat industry and the complexity of international trade relations pose significant challenges to harmonizing food safety standards across countries (Wallace *et al.,* 2018). Therefore, there is an urgent need to enhance monitoring mechanisms, build regulatory capacity, strengthen policy enforcement, and promote global cooperation to ensure responsible antibiotic use and safeguard public health.

Alternative Meat Technologies: Novel meat technologies have gained increasing attention as sustainable solutions to meet global protein demands without adding land-use pressure or driving biodiversity loss (Smetana *et al*., 2023). They also help reduce greenhouse gas emissions from livestock and address safety concerns related to pathogenic bacteria common in traditional meat production (Samad *et al*., 2025). They mimic the sensory, nutritional, and functional properties of meat to a point, but unique to this technology is the capacity to almost eliminate the need to use antibiotics (Samad *et al*., 2024a). Several meat alternatives are being used as substitutes for meat, which are further discussed below and in Fig. 2.

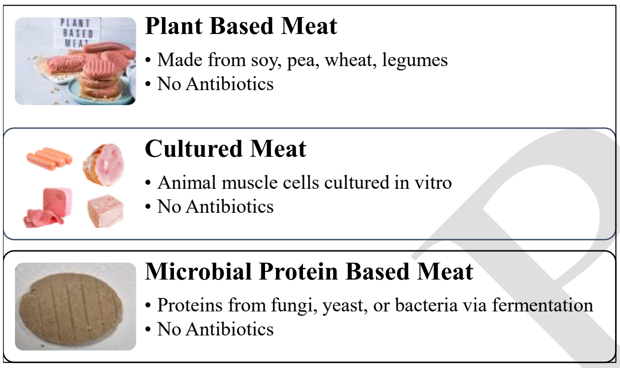

Fig. 2: Meat Alternatives with no Antibiotics.

Plant-Based Meat: Plant-derived meat substitutes offer a promising solution to decrease reliance on antibiotics typically used in livestock production. (Murugaiyan *et al.,* 2022). Plant-based meat addresses key concerns associated with antibiotic use in conventional meat production, such as antibiotic resistance, residue contamination, and environmental pollution, by decreasing the need for livestock farming (Bryant *et al.,* 2021; Kozicka et al., 2023).

Antibiotic Eliminating Mechanism: Plant-based meat products are free from animal-derived components, including those from cattle, poultry, or dairy, and intentionally avoid traditional meat-associated characteristics. They primarily comprise plant proteins sourced from soybeans, peas, lentils, chickpeas, and wheat gluten (Bogueva *et al*., 2023). These raw materials are cultivated without antibiotics at any stage, ensuring that the final products are entirely free from antibiotic residues and resistant bacterial strains (Hwang *et al*., 2020). This effectively disrupts the risk chain associated with animal farming, where antibiotic usage can result in residue presence in meat or environmental contamination through groundwater infiltration. Furthermore, plant-based meats are manufactured in facilities that adhere to strict food safety protocols, eliminating the need for prophylactic or therapeutic antibiotics to control microbial contamination, as is commonly practiced in conventional industrial animal agriculture (Santo *et al*., 2020).

Potential Health Impacts of Plant-Based Meat: Aside from not having antibiotics, plant meat also has a health advantage. These products are generally cholesterol-free and have lower amounts of saturated fat than traditional meat, which helps promote cardiovascular health (Joshi *et al*., 2015). They can also be enriched with fiber, vitamin B12, iron, and zinc by using restructuring technology (Samad *et al*., 2024c), ensuring that they are equal to or potentially better than meat from animals in terms of nutrients (McClements and McClements, 2023). Significantly, removing antibiotics from the food chain protects the gut microbiota and, also maintains the gut health that could otherwise be impaired after continued exposure to antibiotics (Kumar *et al*., 2020).

Consumer Preferences: Consumer awareness and choices have played an important role in the increasing demand for plant-based meat products (Aschemann-Witzel *et al*., 2021). Stronger awareness of antibiotic resistance and increased health-promoting diets drive demand for safer and cleaner protein sources (Tachie *et al*., 2023). Young consumers highly accept plant-based meat for its ethical, environmental, and health-related benefits. Due to rapidly increasing market demand, many large corporations have expanded the variety of their meat analogs to include highly palatable burgers, sausages, nuggets, deli slices, and more products that resemble conventional meat in taste and texture (Future Market Insight, 2025). Various industry reports estimate the global plant-derived meat industry to surpass USD 15.7 billion by 2027, suggesting the continuous acceptance of these products in society and their potential to replace traditional meat as part of every diet (Market and Market, 2022).

Policy and industry integration: As an alternative, plant-based meat has much potential from the policymaking and food security standpoints (Santo et al., 2020). A growing body of evidence suggests that plant-based diets can play a key role in reducing ABR and decreasing the environmental burden of food production (Ferrari et al., 2022). As a result, governmental and public health organizations are progressively acknowledging the role of plant-based diets in combating ABR. In many countries (e.g., the Republic of Korea and the USA), subsidies and research funding have supported innovation and interest in using plant-based foods, especially in urban and institutional settings. At the same time, major food companies recognize that increasing the plant-based offerings in their portfolios makes long-term economic and environmental sense (GFI, 2024). This means that antibiotic-dependent animal meat can be replaced partially or later entirely with scalable plant-based alternatives already in our food systems.

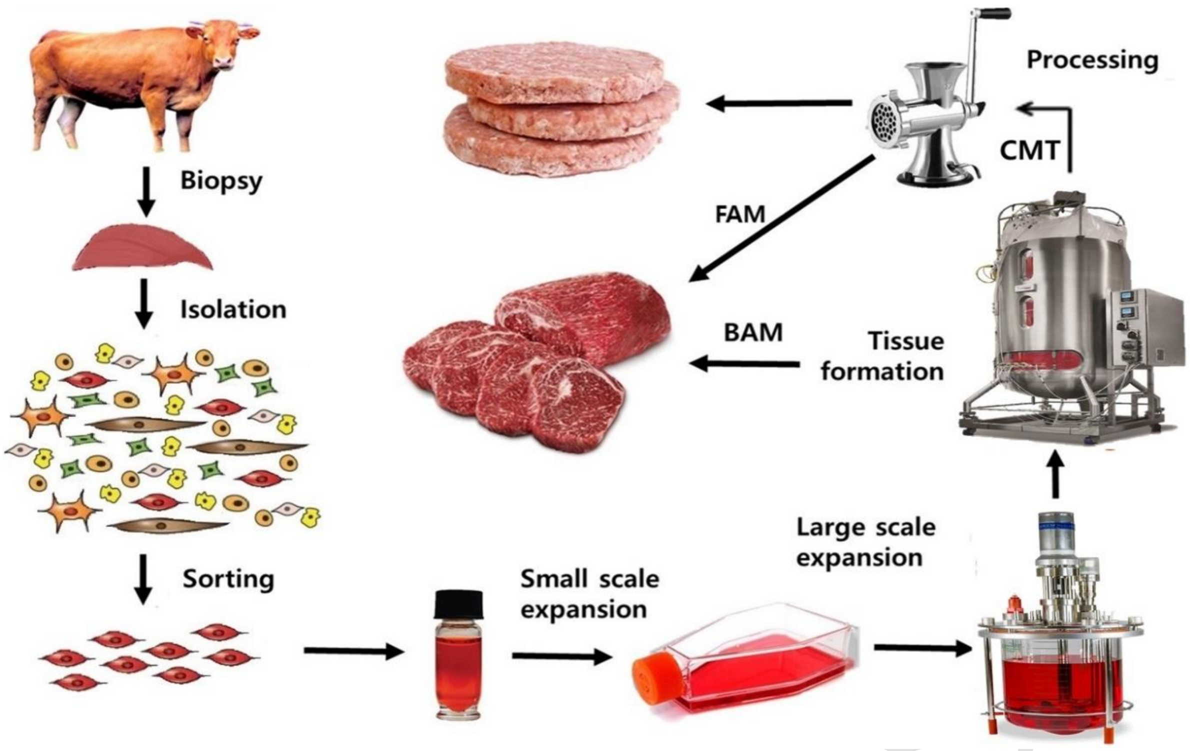

Fig. 3: Cultured meat production process (Adapted from Kim (2021).

Cultured meat: Cultured or lab-grown or cell-based meat is a new technology that can produce meat without animal rearing or slaughter (Samad *et al.,* 2024a). Because cultured meat grows in controlled and sterile environmental conditions, there is limited risk of microbial contamination, and as such, cultured meat can require little to no antibiotics (Chriki & Hocquette, 2020). Hence, cultured meat can be a promising alternative to deal with the problems of antibiotic residues, ABR, and foodborne pathogens.

Production in Sterile Environment: The primary benefit of cultured meat production is that it is produced in sterile, tightly controlled laboratories and bioreactors (Zhang *et al*., 2020). In contrast to traditional livestock routinely challenged with infectious agents, triggering the need for therapeutic or even prophylactic antibiotics, cultured meat is produced in clean facilities where contamination exposure events are substantially reduced (Zhang *et al*., 2020). The development of sterilized environments minimizes or eliminates the requirement for antibiotics during cultured meat production, directly minimizing the chances of harmful antibiotic residues or resistant bacteria incorporated in the food supply chain. For clarity, the production process of cultured meat is described in Fig.3.

Public Health Contributions and Combating ABR: ABR is one of the areas that cultured meat can tackle directly, as the meat production does not require antibiotics (Djisalov *et al*., 2021). The World Health Organization (WHO) has noted that one of the major contributors to the development of pathogens that threaten human health is the widespread use of antibiotics in food-producing animals (World Health Organization, 2023). Cultured meat eliminates a significant source of selective pressure that drives antibiotic resistance by being antibiotic-free altogether due to the absence of antibiotics in cultured meat production. In addition, cultured meat minimizes the risk of zoonotic diseases such as infections with Salmonella and Escherichia coli that are frequently passed on when humans are in close contact with farm animals (Ong *et al*., 2021). With growing consumer demand for sustainably-sourced protein and the critical issues of animal welfare and public health associated with traditional livestock production, cultured meat represents a scalable, sustainable, and modern solution to many of the problems caused by raising animals for food (Samad *et al*., 2024b).

Environmental and Social benefits: Cultured meat offers substantial environmental and social benefits by eliminating the need for large-scale livestock farming (Treich, 2021). It significantly reduces greenhouse gas emissions, land degradation, water consumption, and biodiversity loss associated with conventional meat production (Samad *et al*., 2024b). Socially, cultured meat supports ethical food production by preventing animal slaughter and improving food safety (Alam *et al*., 2024). It also holds potential to enhance global food security by enabling scalable, localized meat production with reduced dependency on traditional agricultural inputs.

Market Readiness and Global Developments: Cultured meat is still at the very beginning of its commercialization. It has received much backing from governments, startups, and traditional food companies, allowing it to hopefully develop faster (Treich, 2021). Authorizations for limited market introductions have been given in countries like Singapore and the United States, and pilot-scale production facilities are being commissioned globally (Kamalapuram *et al*., 2021). Development of bioprocessing technologies, cell culture media, and their economics continues towards advancing the cultured meat industry (Samad *et al*., 2024b).

Furthermore, several challenges are being faced by the cultured meat industry, with the price of cultured meat at the top of the list among these challenges. Thus, these systemic challenges can only be addressed with the close cooperation of food policy stakeholders and biotechnological companies to ensure responsible scale-up, as shown by the ongoing efforts in the cases of Cambodia and Kenya.

Microbial Proteins: Sustainable and Non-Antibiotic Proteins: The classification of single-cell protein is also commonly referred to as microbial protein, and is increasingly recognized as an environmentally sustainable and nutritionally beneficial alternative to conventional meat (Hadi and Brightwell, 2021). In a controlled process, these proteins are made through the fermentation of microorganisms, including bacteria, fungi, algae, and yeast (Bajić *et al.,* 2022). Cultivated independently of livestock, these novel, fully antibiotic-free proteins contribute to mitigating antibiotic resistance (ABR) and offer an environmentally sustainable solution by eliminating waste associated with both human and animal protein production.

Origins and Production Method: Microbial proteins come from a wide variety of microbes, including:

- ✓ Fungi (such as Fusarium venenatum, one of the sources of mycoprotein like Quorn)
- ✓ Yeast (e.g., Candida utilis, Saccharomyces cerevisiae)
- ✓ Bacteria (Methylococcus capsulatus, used for the production of protein-rich biomass)
- ✓ Seaweeds (e.g., Spirulina, Chlorella) (Dalbanjan *et al*., 2024)

Microbial Proteins can be produced using specific microorganisms through submerged liquid or solid-state fermentation, depending on the end product (Manan, 2017). This produces a high-protein biomass in bioreactors in large-scale fermentations with industrially relevant substrates such as carbon dioxide, methane, or agricultural waste streams (Bajić *et al*., 2022). The sterile conditions maintained during production naturally eliminate the need for antibiotics, reduce the cost of operations, and abate the risk of antibiotic residuals.

Nutritional and Functional Value: The amino acid content of microbial proteins is usually high and generally comparable to animal proteins (Singh *et al*., 2020). They also possess the potential to serve as bioavailable sources of vitamins (e.g., vitamin B12 in certain strains), minerals (e.g., iron and zinc), and beneficial lipids (Singh *et al*., 2020). Mycoprotein offers a complete protein and possible metabolic health benefits via fiber content.

The functional properties of microbial proteins are superior in water holding capacity, emulsification, and gelling ability (Ma *et al*., 2022). These properties help them blend well into alternative meat products (patties, nuggets, sausages). Moreover, microbial proteins are versatile in texture and can recreate fibrous meat structures with proper processing (Sha *et al*., 2020).

Environmental and Antibiotic-Free Benefits: The most remarkable benefit of microbial protein manufacturing is its much smaller environmental impact. Specifically, microbial proteins require:

- ✓ Up to 90% less land
- ✓ Significantly reduced water usage
- ✓ Reduced Greenhouse Gas Emissions

The other important point is that there is no antibiotic use, as there are no animals in the animal production processes, which means that antibiotics can end up in food products. Due to the pressure from intensive animal farming, ABR also cannot be an issue. So, their proteins can provide a direct and efficient solution to address the emerging challenge of the world with ABR due to the evolution of traditional meat production.

Industrial Landscape and Market Opportunity: Many companies and research institutions are currently working on microbial meat production technologies. These include mycoprotein-based Quorn (Quorn, 2025), Solar Foods (Solar Foods, 2023), Solein, an air and electricity-powered bacterial protein (Solein, 2025), and NatureFynd's fungus-based protein, sourced from geothermal microbes (NatureFynd, 2025). Such products are becoming popular among consumers who are becoming more aware of health and environmental sustainability. However, significant challenges remain regarding strain engineering, bioreactor design, and consumer acceptance. Advancements in production technologies and consumer awareness are two adequate solutions to overcome the challenges related to microbial proteins production and the market.

Alternative Meat vs. Conventional Meat: Benefits Comparison: As alternative meat technologies evolve, they offer a promising solution to many challenges associated with conventional meat production. These innovations present clear advantages, from improved food safety and environmental sustainability to enhanced public health and ethical considerations. Furthermore, the comparison between alternative and conventional meat is discussed briefly in Table 2.

Challenges and the Future Ahead: While alternative meat technologies offer promising solutions to the challenges of conventional meat production, their widespread adoption is hindered by several barriers. These challenges span technological, regulatory, economic, and social dimensions. Table 3 summarizes the key issues that must be addressed to ensure the successful integration of alternative proteins into global food systems

Future Prospects: The outlook for alternative meat technologies is promising. The future of alternative meat is bright (Samad *et al*., 2025), but it requires more research and improvement of production technologies. Government support, embedding in national dietary guidelines, and public-private partnerships might support accelerated adoption. Thus, a hybrid path of integrating plant, microbial, and cultured products will be the most economically, functionally, and nutritionally affordable option to provide high-quality meat alternatives (Alam *et al*., 2024). Alternative meats are generally not intended to replace traditional meat fully. However, they will complement other critical protein sources such as dairy and fish to support the sustainable and antibiotic-free food production for a growing population.

Table 2: Alternative Meat vs. Conventional Meat: Comparison

Category	Alternative Meat	Conventional Meat
Antibiotic Use	Antibiotic-free production (plant-based, microbial, and cultured meat); eliminates risk of residues and resistant bacteria (Samandari *et al*., 2023)	High antibiotic use for growth promotion and disease prevention; contributes to AMR and residues (Tian *et al*., 2021)
Food Safety	Produced in sterile, controlled environments; lower risk of foodborne pathogens (e.g., *Salmonella*, *E. coli*) (Treich, 2021)	Risk of contamination from pathogens common in slaughterhouses and meat processing (Ovuru *et al*., 2024)
Environmental Impact	Significantly lower GHG emissions, water, and land use; no methane release; supports climate goals (Xu *et al*., 2021)	High resource use; major contributor to GHGs (methane); land degradation and water pollution (Cheng *et al*., 2022)
Nutritional Profile	Lower in saturated fat and cholesterol; can be fortified with nutrients (e.g., B12, omega-3, iron); high fiber content (Neufingerl and Eilander, 2021)	Contains essential nutrients but often high in saturated fats; lacks fiber (Geiker *et al*., 2021)
Public Health	Reduces AMR risk and related infections; lowers healthcare and economic burdens (Samad *et al*., 2024a)	Associated with AMR, foodborne illness, and higher medical costs (Kasimanickam *et al*., 2021)
Animal Welfare	No slaughter in plant/microbial proteins; cultured meat from cell biopsies without killing (Letti *et al*., 2021)	Involves mass breeding, slaughter, and intensive confinement (Samad *et al*., 2024b)
Ethical Considerations	Aligns with ethical consumption trends; avoids animal harm and supports consumer values (Samad *et al*., 2024b)	Raises concerns about animal welfare and industrial farming ethics (Letti *et al*., 2021)
Socioeconomic Innovation	Drives innovation in food tech and biotech; promotes local food systems and sustainable job growth (Herrero *et al*., 2020)	Heavily reliant on global livestock trade; vulnerable to zoonotic outbreaks and market fluctuations Esposito *et al*., 2023)
Global Food Security	Scalable and sustainable; less affected by disease outbreaks and supply shocks (Vo *et al*., 2025)	Vulnerable to pandemics, climate change, and supply chain disruptions (Aguilar-Støen *et al*., 2025)
Alignment with SDGs	Supports several UN SDGs, including zero hunger, good health, responsible consumption, and climate action (Muazzam *et al*., 2025)	Often in conflict with sustainability and public health objectives due to intensive resource use (Xu *et al*., 2021).

Table 3: Key Challenges of Alternative Meat Technologies

Challenge Area	Summary of Key Issues	References
Technology & Manufacturing	Difficulty mimicking taste/texture; scalability issues in cell culture and fermentation	Boukid *et al*., 2021
Regulation & Safety	Lack of global standards; unclear definitions and approval processes	Andersson and Hannah, 2023
Market & Economics	High production costs; limited supply chains; infrastructure gaps in LMICs	Samad *et al*., 2024b
Consumer Acceptance	Concerns about taste, safety, processing, and cultural/religious compatibility	Boukid *et al*., 2021

Conclusions: This review concludes that excessive use of antibiotics for disease prevention and growth promotion in conventional meat production is becoming a global crisis with severe implications on all food security dimensions (availability, access, utilization, and stability), threatening both human health and the sustainability of ecosystems. Antibiotic residues in meat products and ABR bacteria from farming work beyond the agricultural sector, which hampers global public health systems. While some countries have regulatory measures to decrease antibiotic dependence, the impact of these regulations is inconsistent, and the risks involved are still high. In this context, alternative meat technologies showed sustainable solutions. Plant-based products, cultured (lab-grown) meats, fungal, and other microbial proteins are a sustainable and antibiotic-free solution for fulfilling global food demand. These alternatives inherently reduce antibiotic use and increase food safety by decreasing zoonotic pathogens associated with livestock systems. Moreover, they have much lower greenhouse gas emissions, land, and water footprints than their traditional counterparts. Plant-based meat is currently considered the best alternative due to its nutritional benefits and lower price than other alternatives. Alternative meat by category each holds unique benefits but they still face hurdles in technology scaling, consumer adoption, regulation, and price. Overcoming these barriers will necessitate cohesive innovation backed by suitable policies. By overcoming these challenges, meat alternatives can be safe and sufficient for fulfilling the demand of a growing population.

Author's Contribution

Conceptualization: Samad A, Joo ST. Data curation: Samad A, Muazzam A. Methodology: Samad A, Alam AN, Validation: Hwang YH, Joo ST. Investigation: Samad A, Muazzam A. Writing - original draft: Samad A. Writing - review & editing: Samad A, Muazzam A, Alam AN, Hwang YH, Joo ST.

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