TITLE PAGE
- Food Science of Animal Resources -
Upload this completed form to website with submission

ARTICLE INFORMATION	Fill in information in each box below
Article Type	Review Article
Article Title	From Farms to Labs: The New Trend of Sustainable Meat Alternatives
Running Title (within 10 words)	Trends in Sustainable Meat Alternatives
Author	Abdul Samad[1], So-Hee Kim[2], Chan-Jin Kim[3], Eun-Yeong Lee[4], Swati Kumari[5], Md Jakir Hossain[6], AMM Nurul Alam[7], Ayesha Muazzam[8], Young-Hwa Hwang[*9], Seon-Tea Joo[**10]
Affiliation	[1-8, 10] Division of Applied Life Science (BK21 Four), Gyeongsang National University, Jinju, 52828, Korea [9, 10] Institute of Agriculture & Life Science, Gyeongsang National University, Jinju 52828, Korea [9, 10] Orange CAU Co. Ltd, Jinju 52839, Korea
Special remarks – if authors have additional information to inform the editorial office	
ORCID (All authors must have ORCID) https://orcid.org	Abdul Samad 0000-0002-4724-3363 So-Hee Kim 0000-0003-3966-6160 Chan-Jin Kim 0000-0001-5020-6873 Eun-Yeong Lee 0000-0002-3467-7349 Swati Kumari 0009-0001-3330-7821 Md Jakir Hossain 0009-0008-7663-9202 AMM Nurul Alam 0000-0003-3153-3718 Ayesha Muazzam 0000-0002-5155-6629 Young-Hwa Hwang 0000-0003-3687-3535 Seon-Tea Joo 0000-0002-5483-2828
Conflicts of interest List any present or potential conflict s of interest for all authors. (This field may be published.)	The authors declare no potential conflict of interest.
Acknowledgements State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available. (This field may be published.)	This study is supported by the National Research Foundation of Korea (NRF) under a grant funded by the Korean government (MSIT) (No. 2020R1I1A2069379 and 2023R1A2C1004867).
Author contributions (This field may be published.)	Conceptualization: Samad A, Hwang YH, Joo ST Data curation: Samad A, Kim SH, Kim CJ Methodology: Samad A, Lee EY, Kumari S Software: Hossain MJ, Alam AN, Muazzam A Validation: Joo ST, Hwang YH Investigation: Samad A, Kim SH, Muazzam A Writing - original draft: Samad A Writing - review & editing: Samad A, Kim SH, Kim CJ, Lee EY, Kumari S, Hossain MJ, Alam AN, Muazzam A, Hwang YH, Joo ST
Ethics approval (IRB/IACUC) (This field may be published.)	This article does not require IRB/IACUC approval because there are no human and animal participants.

CORRESPONDING AUTHOR CONTACT INFORMATION

For the corresponding author (responsible for correspondence, proofreading, and reprints)	**Fill in information in each box below**
First name, middle initial, last name	Young-Hwa Hwang Seon-Tea Joo
Email address – this is where your proofs will be sent	philoria@gnu.ac.kr stjoo@gnu.ac.kr
Secondary Email address	
Postal address	Division of Applied Life Science (BK21 Four), Gyeongsang National University, Jinju 52828, Korea
Cell phone number	
Office phone number	+82-55-772-1943
Fax number	+82-55-772-1949

From Farms to Labs: The New Trend of Sustainable Meat Alternatives

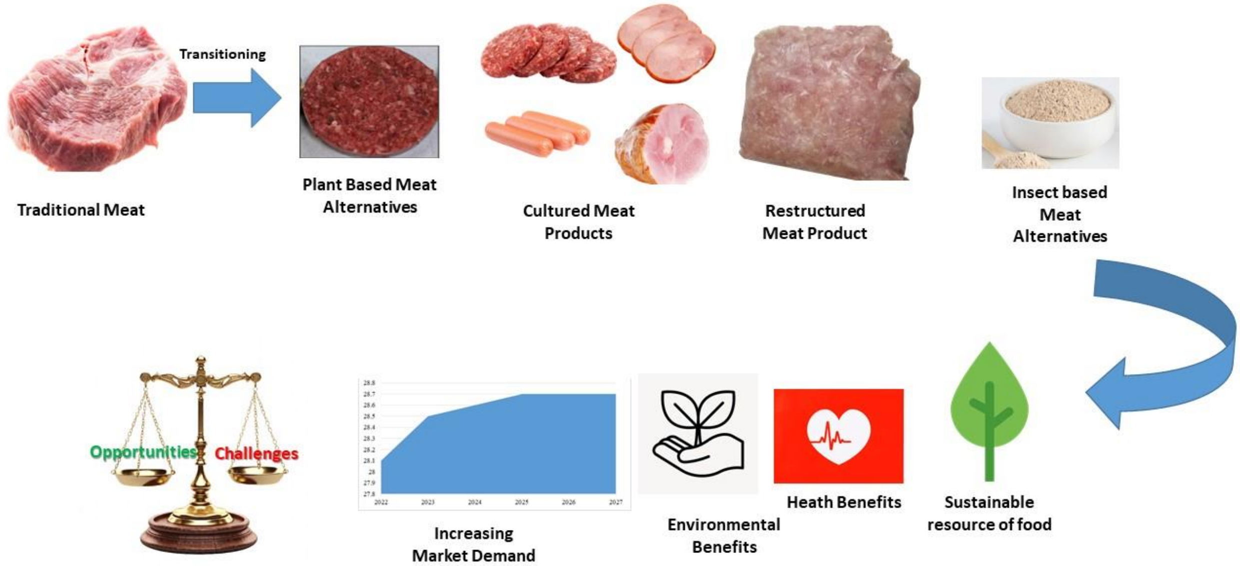
Abstract:

Meat analogs or meat alternatives mimic conventional meat by using non-meat ingredients. There are several reasons for the rising interest in meat alternatives, e.g., health-consciousness, environmental concerns, and the growing demand for sustainable diets. Factors like low-calorie foods, low-fat, efforts to reduce greenhouse gas emissions, and flexitarian lifestyles are also contributing to this change (conventional to meat analogs). Numerous meat substitutes are presently being launched in alternative meat markets. Plant-based meat, restructured meat, cultured meat, hybrid cultured meat, and insect protein-based meat are prevalent among meat alternatives. The scope of meat alternatives, including plant-based meat, cultured meat, restructured meat, and insect-based protein products, is expanding due to advances in food technology. Innovation in food technology plays a crucial role in sustainable food production. Still, there are some challenges to the market of meat alternatives, including consumer acceptance, the appearance of meat alternatives, and the cost of production. Innovative approaches, such as advanced technologies and awareness of meat alternatives to the meat consumer, are required to deal with these challenges. This review briefly examines the technological advances, regulatory requirements, pros and cons, and market trends of meat alternatives. The finding of this review highlights the importance of meat alternatives as a sustainable resource of food. Moreover, meat alternatives can fulfill the increasing demand for meat and also decrease the environmental impact. Additionally, this review also explores ways to improve the overall market scenario of meat alternatives.

Key Words

Meat Analog, Environmental impact, Cultured meat, Plant-Based Meat Alternatives, Restructured meat, Insect protein-based meat

Graphical Abstract



Introduction

History of using meat as an important component of human diet is 2.6 million years old (Heidemann et al., 2020). Initially, humans hunted animals, but after sometime, to facilitate the free access to meat, human started domesticating birds and livestock, including pigs, chicken and cattle. The world population is increasing day by day. There are 8.1 billion people who are currently living on this planet (FAO, 2015), and it is predicted that by 2050, this number will touch 9.7 billion (FAO, 2015); further, by 2080, the number of people on this planet will be 10.4 billion (FAO, 2015) while the trend of increasing population is shown in **Figure 1.** The FAO-UNO stated that a significant challenge in meeting demand of food would arise due to lack of food resources while the demand is projected to increase by 70% due to the growing global population (FOA, 2009). These chellenges elevated the r Many alternatives are being used in place of meat to cover some portion of meat demand, e.g., Plant-based meat (Bakhsh et al., 2021a; Kumari et al., 2023; Samad et al., 2024a), Restructured meat (Samad et al., 2024b), Cultured meat (Samad et al., 2024c; Kim et al., 2024), Hybrid cultured meat (Alam et al., 2024). Mycoprotein Meat Alternatives (Shahid et al., 2024) and insect-based protein alternatives (Anusha et al., 2023).

As the search for sustainable and efficient food sources intensifies, the meat industry is undergoing a significant transformation with the rise of lab-grown and alternative proteins (Mylan et al., 2023). This change shows a growing awareness of the environmental and ethical implications of conventional meat production. Cultivated or cell-based meat shows an innovative approach where there is no need to slaughter animals, as in cultivated or cultured meat, animal cells are grown in controlled conditions to produce meat (Soleymani et al., 2024). This method not only has the potential to reduce land use and greenhouse gas emissions but also has a positive correlation with animal welfare in terms of minimizing the requirement of rearing animals in livestock farms (Treich, 2021).

In addition to cultivated meat, other meat alternatives are also progressing, such as plant-based meats. Plant-based products are rapidly growing because of their climate-friendly nature and health benefits (Dueñas-Ocampo et al., 2023). Hybrid cultured meat, which has conventional meat with cultured cells, accommodates traditional and lab-grown ways (Alam et al., 2024). Simultaneously, proteins derived from insects and fungi-based mycoproteins are becoming more useful sources of protein and can be used as meat alternatives because of their health benefits and less environmental impact than traditional meat production (Anusha et al., 2023). This progress shows a crucial step toward resolving the demanding problem of the increasing worldwide population and demand for reliable food systems (Galanakis, 2024). With changes in technology and customer choices, the future of various alternatives to meat ensures the provision of a great range of options that can fulfill the nutritious needs of billions, along with encouraging environmental handling and moral practices.

This review explores the revolutionary landscape of different meat alternatives, with a focus on technological advancement and novel approaches that are revolutionizing the future of food. This review brings light on the various meat alternatives, insect-based meats, cultured meat, plant-based meat, and hybrid options. This review contains ways of production, environmental impacts, and their ability to cope with increasing worldwide food demand. By assessing the pros and cons linked with each alternative, this review aims to provide a detailed comprehension of the emerging technologies that could contribute to a more reliable and ethical food system. This thorough analysis will guide future research and decision-making in food science and sustainability.

2. From Farm to Lab

There are various factors, including environmental concerns, health benefits, and animal welfare, have driven the shift from traditional farming to meat alternatives (de Boer & Aiking, 2022). Meat analogs are also described as mock meat and imitation meat. The process of replacing meat in food products is not entirely new; it was started at the beginning of the 1960s (Ismail et al., 2020). Usually, soy proteins in tofu and tempeh (fermented cake of soybean) are widely used in meat analogs. These components have undergone processing and have been utilized for centuries as traditional cuisines in Southeast Asia since as early as 956 CE (Gopi et al., 2023). In addition to these traditional Asian products, texturized vegetable protein (TVP) obtained from pressed defatted soy meals, wheat gluten, and concentrates from soy protein were first introduced as a meat analog (Bauneet al., 2022). The launch of this texturized vegetable protein (TVP) as an alternative to meat arose in the second half of the 20th century (Bakhsh et al., 2021b).

TVP has an elastic and foamy texture and is suitable for use as a meat alternative (Zimberoff et al., 2021). Usually, TVP is made from soybeans. Texturized soy protein (TSP), due to its meat-like surface attributes, is an exceptionally universal food component, and protein quality is also similar to animal proteins (Bakhsh et al., 2022). Although vegetable protein components are cost-effective sources, they can be altered into amazing meat alternatives such as preserved meat (Kurek et al., 2022), meat alternatives in beef patties, and pet meals (Jiang et al., 2020). However, adopting plant-based diets could be challenging for some people (Canseco-Lopez & Miralles, 2023). There may be various associated challenges, such as an intense off-taste for soybean-extracted products (Zioga et al., 2022). The taste is due to isoflavones, saponins, and lipoxygenase activity, which reduce the use of soy-based protein as a meat alternative (wang et al., 2022). The other major concern is the allergic effect of food protein in legume crops such as common beans, lentils, and soybeans (Abu et al., 2024), which has limited the development of meat analogs from these plant-based sources. Furthermore, cereal proteins such as wheat, rye, barley, etc., are also toxic for individuals with gluten intolerance.

At the beginning of the 21st century, due to the demand for healthy food, meat analogs became popular. The reliable implications of consumers' diets continuously arise along with other choices for traditional meat (Lawrence & King, 2019). During the last 10 years, recent technological advancements in food science and its manufacturing have been introduced in meat alternative products that have the potential to imitate the flavor, appearance, texture, and functionality of traditional meat-based products (Lawrence & King, 2019). Currently, the main focus is on the direct manufacturing of novel protein sources in meat alternatives such as lab-based and plant-based meat. This advanced technology will help to cope with the restrictions of using traditional protein-based, specifically from cereals and legumes. In recent years, edible insects have been expected to be a good alternative to human foods because of their good fat content and high protein content. The Supermarket chain in Germany and Switzerland had already started selling balls of mealworms and burger patties of insects. However, in North America and Europe, an increasing number of insect-based protein products for human intake have also been reported (Verbeke et al., 2015).

2.1. Plant-Based Meat Alternatives

Plant-based meat alternatives are good protein sources, and their continuity, nutritional value, color, and taste are similar to conventional meat (Kumari et al., 2023). Conventionally, plant-derived meat alternatives are manufactured based on years-old protocols (Joshi & Kumar, 2015). To make a final product that seems like meat, soy-based proteins, lentils, rice, wheat gluten, and mushrooms were all processed with meat-like taste additives (Joshi & Kumar, 2015). Soybean-derived tempeh and tofu are the most common plant-based meat alternatives. Different plant-based proteins, such as gluten from wheat, are also used in traditional foods such as seitan (Dekkers et al., 2016). Plant-based meat alternative analogs are based upon textured vegetable protein (TVP), an extensive dry product that is derived from soy constituents (Boukid, 2024). Analogous substances are those that have the same structure as each other but differ slightly in their makeup [40]. Mimic meat or meat alternative in this situation is a food provision that looks similar in structure but significantly differs in its makeup (Bohrer, 2019). Meat substitution, vegetarian meat, meat alternative, amalgam meat, mimic meat, processed meat, or plant-based meat are the terms used alternatively (Rooney & Muller 2023). Mock meat also has almost the same properties, such as consistency, flavor, and texture, and it also has chemical-based properties similar to different kinds of meat (Adam et al., 2024).

Due to the global demand for reliable meals as a result of animal-based foods involvement as well as other environmental factors, organizations have enlarged their focus on manufacturing meat alternatives (Henchion et al., 2021). The market for alternative meat depends upon meat reducers; meat reducers are the consumers who are interested in maintaining weight and health (Apostolidis et al., 2016). There are several health benefits of eating meat alternatives, and lowering meat intake may prove helpful in reducing cholesterol levels and also minimizing cardiac problems; daily original meat intake is linked with colorectal cancer. Researcher's interest in plant-based meat is increasing due to high demand by consumers because of health issues connected with daily meat intake or due to obligatory consumption of vegetable-based diets in specific religious sects. New technologies that are developed in the sector of plant-based meat alternatives are explained in **Table 1.**

2.2. Restructured Meat

The conversion of different ingredients, including meat or vegetable protein, into an innovative product with enhanced nutritional value is termed as restructured meat (RM) (Samad et al., 2024b). The composition of RM is depends upon the binding agents as these agents are responsible for the proper texture or structure of final product (Carpentieri et al., 2022). The potential of RM relates to the sustainability of the meat business by utilizing less used meat cuts or by-products that are being wasted due to no or less demand. RM is an opportunity to combine less used parts of meat components with traditional, inexpensive sources of plant protein to develop a new product with good physiochemical properties. Various methods, such as meat restructuring and hybrid meat (HBM), have been utilized to transform meat in order to integrate health benefits (functional components) from alternative sources, including plants (Mireles-Arriaga et al., 2017) and other protein sources (Baugreet et al., 2018). RM may serve as an advantageous option for health-conscious individuals seeking to diminish their meat consumption. **Figure 3** delineates the process of restructured meat. **Table 2** delineates recent trends in restructured meat output.

Cultured Meat

One of the most sustainable options is cultured meat. The expansion of stem cells facilitates the generation of cultured meat. In 1894, French scientist Marcellin Berthelot proposed the notion of generating food products by culturing techniques, contending that industrial facilities could manufacture eggs, dairy, and meat (Shapiro, 2024). The cultivation of food products began in 1894. Self-replicating steaks were described by British India Secretary Frederick Smith in 1930. It was proposed that meat may be produced on a large scale using progenitor cells (Kirsch et al., 2023). In the UK, Gregory Sims produced and commercialized the first plant-based burger in 1982, establishing the foundation for the production of meat replacements (Woodholme Cardiovascular Associates, 2020). In 1995, the Food and Drug Administration (FDA) approved culturing or in-vitro techniques for cost-effective meat production (Stephens et al., 2019). The first commercially viable production of cultured beef occurred in 1999 (Kirsch et al., 2023). In 2013, Mark Post first developed grown meat with bovine muscle cells as the major source at Maastricht University, Netherlands (The Guardian, 2013). Consequently, numerous researchers initiated their investigations into cultured meat production. **Figure 4** elucidates the process of cultured meat. **Table 3** shows the recent technological advancements in cultured meat production.

Insect Based Protein Alternatives

Insect-derived meat substitutes are emerging as a sustainable and healthy alternative to conventional meat (Anusha et al., 2023). Insects are abundant in protein, vital amino acids, omega-3 and omega-6 fatty acids, iron, and zinc (Oonincx & Finke, 2021). They necessitate reduced area, water, and feed relative to conventional livestock and emit fewer greenhouse gases (Van et al., 2017). Notwithstanding these advantages, consumer adoption continues to pose a difficulty, especially in Western nations, owing to issues such as food neophobia and unfamiliarity (Siddiqui et al., 2022). Nonetheless, heightened awareness of their nutritional and environmental advantages may enhance acceptability. Insects can be transformed into diverse forms and integrated into goods such as protein bars, snacks, and restructured meat (Borges et al., 2022).

Insects are a significant source of nutrients. They comprise 13-77% protein by dry weight, rendering them a highly effective protein source (Sujatha et al., 2024). The protein content fluctuates based on the species and developmental stage. Crickets and mealworms are notably rich in protein (Stone et al., 2019). Besides protein, insects offer vital amino acids that are required for human health. Lysine, methionine, and cysteine are frequently deficient in plant-based diets. Moreover, insects are abundant in healthful lipids, encompassing omega-3 and omega-6 fatty acids, which are advantageous for cardiovascular health. They also encompass vital micronutrients, including iron, zinc, magnesium, and B vitamins, which are crucial for numerous physiological activities (Oonincx & Finke, 2021).

A primary justification for exploring insect-based meat replacements is their little environmental impact. Conventional cattle agriculture is resource-demanding, necessitating substantial quantities of land, water, and feed. Conversely, insect farming exhibits remarkable efficiency. Insects can be cultivated on organic waste, so diminishing the necessity for feed and contributing to waste management. They necessitate considerably less water and area than cattle, pigs, and chickens.

Producing 1 kg of insect protein takes around 2 liters of water, while the equivalent quantity of animal protein demands almost 15,000 liters of water.

Moreover, insects emit significantly lower amounts of greenhouse gases. Animals such as cattle are the main source of methane and nitrous oxide emission while both are the powerful greenhouse gases. On the other hand, insects produce less gases, which is making them a more environmentally sustainable option. Insects can be transformed into diverse forms to enhance their palatability and versatility. They can be pulverized into powders, which may subsequently serve as components in various food products. Ongoing research and development, coupled with heightened consumer awareness, may enable insect-based meals to emerge as a predominant protein source in the future. **Table 4** shows the recent trends in insect-based Protein alternatives

Market Trends of Meat Alternatives

Plant-Based Meat

The global plant-based meat market was valued at $6.1 billion in 2022, with significant growth in regions like Latin America and Europe (Caputo et al., 2024). Despite a slight decline in U.S. retail sales, the long-term trend shows a tripling of sales over the past decade. The category has opportunities to improve consumer engagement by focusing on taste parity, affordability, and effectively communicating health benefits. The trend of the plant-based meat market is shown in **Figure 5**

2. Restructured Meat

Market Insights: Restructured meat products, which include plant-based and hybrid meat products, are gaining traction due to their ability to mimic the texture and taste of conventional meat (Rai et al., 2023). Innovations in this category are driven by advancements in food technology and consumer demand for healthier and more sustainable options. Market trends of restructured meat are elaborated in **Table 5**.

3. Cultured Meat

Market Potential: Cultured meat, also known as lab-grown meat, is still in its nascent stages but holds significant promise (Chodkowska et al., 2022). The market is projected to grow as regulatory approvals increase and production costs decrease. Companies are focusing on scaling up production and improving the taste and texture to match conventional meat. While consumer acceptance is gradually increasing, there are still challenges related to perception and cost. The market scenario of cultured meat is elaborated in **Figure 6.**

4. Insect-Based Meat

Insect-based meat is emerging as a sustainable and protein-rich alternative (Malila et al., 2024). The market is expected to grow as consumers become more aware of the environmental benefits and nutritional value of insect protein (Khayrova et al., 2024).

Comparison of meat alternatives

We compare meat alternatives based on available references. The comparison is shown in **Table 6**

Challenges and Opportunities in the sector of meat alternatives

Several challenges and opportunities in the meat alternatives sector may affect the overall market. Challenges and opportunities are briefly explained in **Table 7.**

Future Prospects

The future of meat alternatives is bright, driven by technological innovations, market expansion, and a growing focus on sustainability and ethics (Nadathur et al., 2024). Advances in cultured and plant-based meat technologies are making these products more affordable and appealing, while insect-based proteins are gaining mainstream acceptance (Rehman et al., 2024). The market is expanding globally, targeting health-conscious consumers and flexitarians. Environmental benefits, such as reduced resource use and lower emissions, along with ethical considerations, are key drivers (Pang & Chen, 2024). Government initiatives and public awareness campaigns are also supporting this growth, making meat alternatives a promising solution for a sustainable and ethical food future (Rehman et al., 2024).

Conclusion

The meat alternatives market is positioned for substantial expansion, propelled by the demand for sustainable and ethical food options. Technological advancements in cultured, plant-based, and insect-based meats are enhancing the attractiveness and accessibility of these products for customers. Notwithstanding problems, including production expenses, regulatory obstacles, and customer acceptance, the prospects for environmental sustainability, health advantages, and market growth are considerable. With ongoing advancements in research and development, meat substitutes are anticipated to be pivotal in fulfilling global protein demands while mitigating the environmental consequences of conventional meat production. The prospects for meat alternatives are promising, with the capacity to revolutionize the food business and foster a more sustainable and ethical food system.

Acknowledgment

This study is supported by the National Research Foundation of Korea (NRF) under a grant funded by the Korean government (MSIT) (No. 2020R1I1A2069379 and 2023R1A2C1004867).

References

3D Print.com. 2021. 7 3D Printed Veggie Meats Rebuilding the Meat Industry. Available From: https://3dprint.com/290619/7-3d-printed-veggie-meats-rebuilding-the-meat-industry/. Accessed at Aug 3, 2024.

Abu Risha M, Rick EM, Plum M, Jappe U. 2024. Legume Allergens Pea, Chickpea, Lentil, Lupine and Beyond. Curr Allergy Asthma Rep 11:1-22.

Adam AB, Abubakar MY, Aneshi A, Abdullahi S, Ataitiya H, Garba F. 2024. Comparative Studies and Proximate Analysis of Brown Beans as a Plant-Based Meat Alternative. Int J Chem 43:38-45.

Alam AN, Kim CJ, Kim SH, Kumari S, Lee SY, Hwang YH, Joo ST. 2024. Trends in hybrid cultured meat manufacturing technology to improve sensory characteristics. Food Sci Anim Resour 44:39-50.

Anusha Siddiqui S, Bahmid NA, Mahmud CM, Boukid F, Lamri M, Gagaoua M. 2023. Consumer acceptability of plant-, seaweed-, and insect-based foods as alternatives to meat: A critical compilation of a decade of research. *Crit Rev Food Sci Nutr* 63:6630-6651.

Apostolidis C, McLeay F. 2016. It's not vegetarian, it's meat-free! Meat eaters, meat reducers and vegetarians and the case of Quorn in the UK. Social Business 6:267-290.

Auyeskhan U, Azhbagambetov A, Sadykov T, Dairabayeva D, Talamona D, Chan MY. 2024. Reducing meat consumption in Central Asia through 3D printing of plant-based protein—enhanced alternatives—a mini review. Front nutr 10:1308836.

Badekila AK, Kini S, Jaiswal AK. 2021. Fabrication techniques of biomimetic scaffolds in three-dimensional cell culture: A review. J Cell Physiol 236:741-762.

Bakhsh A, Lee EY, Ncho CM, Kim CJ, Son YM, Hwang YH, Joo ST. 2022. Quality characteristics of meat analogs through the incorporation of textured vegetable protein: A systematic review. Foods 11:1242.

Bakhsh A, Lee SJ, Lee EY, Hwang YH, Joo ST. 2021a. Traditional plant-based meat alternatives, current, and future perspective: a review. J Agric Life Sci 55:1-10.

Bakhsh A, Lee SJ, Lee EY, Sabikun N, Hwang YH, Joo ST. 2021b. A novel approach for tuning the physicochemical, textural, and sensory characteristics of plant-based meat analogs with different levels of methylcellulose concentration. Foods 10:560.

Baugreet S, Kerry JP, Allen P, Gallagher E, Hamill RM. 2018. Physicochemical Characteristics of Protein-Enriched Restructured Beef Steaks with Phosphates, Transglutaminase, and Elasticised Package Forming. J Food Qual 2018:4737602.

Baune MC, Terjung N, Tülbek MÇ, Boukid F. 2022. Textured vegetable proteins (TVP): Future foods standing on their merits as meat alternatives. Future Foods 6:100181.

Bohrer BM. 2019. An investigation of the formulation and nutritional composition of modern meat analogue products. Food Sci Hum Wellness 8:320-329.

Borges MM, da Costa DV, Trombete FM, Câmara AK. 2022. Edible insects as a sustainable alternative to food products: An insight into quality aspects of reformulated bakery and meat products. Curr Opin Food Sci 46:100864.

Boukid F. 2024. Texture enhancement strategies of plant-based meat and drinks alternatives. In Handbook of Plant-Based Food and Drinks Design. Academic Press. pp. 285-296.

Campagnol PC, Lorenzo JM, Teixeira A, Santos EM, Andrés SC, Dos Santos BA, Pinton MB, Leães YS, Cichoski AJ. 2023. The nutritional characteristics and health-oriented advances of meat and meat products. In Meat and Meat Replacements. Woodhead Publishing. pp 111-144.

Canseco-Lopez F, Miralles F. 2023. Adoption of Plant-Based Diets: A Process Perspective on Adopters' Cognitive Propensity. Sustainability. May 5;15(9):7577.

Caputo V, Sun J, Staples AJ, Taylor H. Market outlook for meat alternatives: Challenges, opportunities, and new developments. Trends in Food Science & Technology. 2024 Apr 16:104474.

Carpentieri S, Larrea-Wachtendorff D, Donsi F, Ferrari G. 2022. Functionalization of pasta through the incorporation of bioactive compounds from agri-food by-products: Fundamentals, opportunities, and drawbacks. Trends Food Sci Technol 122:49-65.

Chodkowska KA, Wódz K, Wojciechowski J. 2022. Sustainable future protein foods: the challenges and the future of cultivated meat. Foods 11:4008.

Choudhury D, Singh S, Seah JS, Yeo DC, Tan LP. 2020. Commercialization of plant-based meat alternatives. Trends Plant Sci 25:1055-1058.

de Boer J, Aiking H. 2022. Considering how farm animal welfare concerns may contribute to more sustainable diets. Appetite 168:105786.

Dekkers BL, Nikiforidis CV, van der Goot AJ. 2016. Shear-induced fibrous structure formation from a pectin/SPI blend. Innov Food Sci Emerg Technol 36:193-200.

Dueñas-Ocampo S, Eichhorst W, Newton P. 2023. Plant-based and cultivated meat in the United States: a review and research agenda through the lens of socio-technical J Clean Prod 405:136999.

Dvorak N, Liu Z, Mouthuy PA. 2024. Soft bioreactor systems: a necessary step toward engineered MSK soft tissue?. Front Robot AI 11:1287446.

FAO. 2015. World hunger falls to under 800; eradication is the next goal. FAO News 27, May 2015. Available From: https://www.wfp.org/news/news-release/world-hunger-falls-under-800-million-eradication-next-goal-0. Accessed at July 20, 2024.

FAO. 2009. Global Agriculture Towards 2050. Available From: https://www.fao.org/fileadmin/user_upload/lon/HLEF2050_Global_Agriculture.pdf Accessed at July 22, 2024

Ford H, Zhang Y, Gould J, Danner L, Bastian SE, Yang Q. 2024. Comparing motivations and barriers to reduce meat and adopt protein alternatives amongst meat-eaters in Australia, China and the UK. Food Qual Prefer 118:105208.

Gadekar YP, Sharma BD, Shinde AK, Mendiratta SK. Restructured meat products-production, processing and marketing: a review. Indian J Small Rumin 21:1-12.

Galanakis CM. 2024. The future of food. Foods 13:506.

Gasco L, Acuti G, Bani P, Dalle Zotte A, Danieli PP, De Angelis A, Fortina R, Marino R, Parisi G, Piccolo G, Pinotti L. 2020. Insect and fish by-products as sustainable alternatives to conventional animal proteins in animal nutrition. Ital J Anim Sci 19:360-372.

Giezenaar C, Orr RE, Godfrey AJ, Maggs R, Foster M, Hort J. 2024. Profiling the novel plant-based meat alternative category: Consumer affective and sensory response in the context of perceived similarity to meat. Int Food Res 188:114465.

Gómez I, Janardhanan R, Ibañez FC, Beriain MJ. 2020. The effects of processing and preservation technologies on meat quality: Sensory and nutritional aspects. Foods 9:1416.

GOPI G, PM MK, NANDANA M, SALEEKA F, SABU AR, GK R. 2023. Development and Evaluation of Jackfruit-Based Meat Analogue by Extrusion Technology. MSc. Thesis, Department of Processing and Food Engineering, Kelappaji College of Agricultural Engineering and Technology, Kerala, India.

Gradl K, Hernández AS, Grayson WL, Finnigan TJ, Theobald HE, Kashi B, Somoza V. 2024. What Technological and Economic Elements Must be Addressed to Support the Affordability, Accessibility, and Desirability of Alternative Proteins in Low-and Middle-Income Countries?. Curr Dev Nutr 8:102027.

Grasso S, Bordiga M. 2023. Startups. In Edible Insects Processing for Food and Feed. CRC Press. (pp. 133-154).

Guyony V, Fayolle F, Jury V. 2023. High moisture extrusion of vegetable proteins for making fibrous meat analogs: A review. Food Rev Int 39:4262-4287.

Han W, Kong L, Xu M. 2022. Advances in selective laser sintering of polymers. Int J Extreme Manuf 4:042002.

Heidemann MS, Molento CF, Reis GG, Phillips CJ. 2020. Uncoupling meat from animal slaughter and its impacts on human-animal relationships. Front psychol 11:535710.

Henchion M, Moloney AP, Hyland J, Zimmermann J, McCarthy S. 2021. Trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. Animal 15:100287.

Howard PH. 2019. Corporate concentration in global meat processing: The role of feed and finance subsidies. In: Global meat: Social and environmental consequences of the expanding meat industry. 1st ed. D'Silva J, Webster J (ed). Routledge, New York, NY, USA. pp 31-53.

Ismail I, Hwang YH, Joo ST. 2020. Meat analog as future food: A review. J Anim Sci Technol 62:111.

Jiang G, Ameer K, Kim H, Lee EJ, Ramachandraiah K, Hong GP. 2020. Strategies for sustainable substitution of livestock meat. Foods 9:1227.

Joshi VK, Kumar S. 2015. Meat Analogues: Plant based alternatives to meat products-A review. Int J Food Ferment Technol 5:107-119.

Kafle A, Luis E, Silwal R, Pan HM, Shrestha PL, Bastola AK. 2021. 3D/4D printing of polymers: fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA). Polymers 13:3101.

Kirsch M, Morales-Dalmau J, Lavrentieva A. 2023. Cultivated meat manufacturing: Technology, trends, and challenges. Eng Life Sci 23:e2300227.

Kumar MB, Sathiya P, Varatharajulu M. 2021. Selective laser sintering. In: *Advances in Additive Manufacturing Processes.* 1st ed. Beijing, China: Bentham Books. pp 28.

Kumari S, Alam AN, Hossain MJ, Lee EY, Hwang YH, Joo ST. 2023. Sensory evaluation of plant-based meat: Bridging the gap with animal meat, challenges and future prospects. Foods. 13:108.

Kumari S, Kim SH, Kim CJ, Hwang YH, Chung YS, & Joo ST. 2024. Development and comparative evaluation of imitated fiber from different protein sources using wet-spinning. Food Sci Anim Resour 4:1156-1166.

Kurek MA, Onopiuk A, Pogorzelska-Nowicka E, Szpicer A, Zalewska M, Półtorak A. 2022. Novel protein sources for applications in meat-alternative products—Insight and challenges. Foods 11(7):957.

Lawrence S, King T. 2019. Meat the alternative: Australia's $3 B opportunity. Food Frontier. Available From: https://www.foodfrontier.org/wp-content/uploads/2019/09/Food-Frontier-Meat-the-Alternative-2019-State-of-the-Industry.pdf. Accessed at: Aug 1, 2024

Lee SH, Choi J.2024. The Need for Research on the Comparison of Sensory Characteristics between Cultured Meat Produced Using Scaffolds and Meat. Food Sci Anim Resour 44:269-283.

Lin X, Wang F, Lu Y, Wang J, Chen J, Yu Y, Tao X, Xiao Y, Peng Y. 2023. A review on edible insects in China: Nutritional supply, environmental benefits, and potential applications. Cur Res Food Sci 7:100596.

Liu P, Song W, Bassey AP, Tang C, Li H, Ding S, Zhou G. 2023. Preparation and quality evaluation of cultured fat. J Agric Food Chem 71:4113-4122.

Malila Y, Owolabi IO, Chotanaphuti T, Sakdibhornssup N, Elliott CT, Visessanguan W, Karoonuthaisiri N, Petchkongkaew A. 2024. Current challenges of alternative proteins as future foods. npj Sci Food 8(1):53.

Martins B, Bister A, Dohmen RG, Gouveia MA, Hueber R, Melzener L, Messmer T, Papadopoulos J, Pimenta J, Raina D, Schaeken L. 2024. Advances and challenges in cell biology for cultured meat. Annu Rev Anim Biosci 12:345-368.

McClements IF, McClements DJ. 2023. Designing healthier plant-based foods: Fortification, digestion, and bioavailability. Food Res Int 169:112853.

Megido RC, Francis F, Haubruge E, Le Gall P, Tomberlin JK, Miranda CD, Jordan HR, Picard CJ, Pino MJ, Ramos-Elordy J, Katz E. 2024. A worldwide overview of the status and prospects of edible insect production. Entomol Gen 44:3-27.

Mireles-Arriaga AI, Ruiz-Nieto JE, Juárez-Abraham MR, Mendoza-Carrillo M, Martínez-Loperena R. 2017. Functional restructured meat: Applications of ingredients derived from plants. Vitae 24:196-204.

Molfetta M, Morais EG, Barreira L, Bruno GL, Porcelli F, Dugat-Bony E, Bonnarme P, Minervini F. 2022. Protein sources alternative to meat: state of the art and involvement of fermentation. Foods 11(14):2065.

Molina JR, Frías-Celayeta JM, Bolton DJ, Botinestean C. 2024. A Comprehensive Review of Cured Meat Products in the Irish Market: Opportunities for Reformulation and Processing. Foods 13:746.

Mylan J, Andrews J, Maye D. 2023. The big business of sustainable food production and consumption: Exploring the transition to alternative proteins. Proc Natl Acad Sci 120:e2207782120.

Nadathur S, Wanasundara JP, Scanlin L. 2024. Feeding the globe nutritious food in 2050: Obligations and ethical choices. In Sustainable Protein Sources Academic Press. pp 649-668.

Niszczota P, Błaszczyński J. 2024. Hard to digest investments: People oppose investment in both conventional and cultured meat producers. Ecol Econ 218:108094.

Oonincx DG, Finke MD. 2021 2021. Nutritional value of insects and ways to manipulate their composition. J Insects Food Feed 7(5):639-659.

Pang S, Chen MC. 2024. Investigating the impact of consumer environmental consciousness on food supply chain: The case of plant-based meat alternatives. Technol Forecast Soc Change 201:123190.

Piercy E, Verstraete W, Ellis PR, Banks M, Rockström J, Smith P, Witard OC, Hallett J, Hogstrand C, Knott G, Karwati A. 2023. A sustainable waste-to-protein system to maximise waste resource utilisation for developing food-and feed-grade protein solutions. Green Chem.;25(3):808-32.

Pintado T, Delgado-Pando G. Towards more sustainable meat products: Extenders as a way of reducing meat content. Foods. 2020 Aug 3;9(8):1044.

Rai A, Sharma VK, Sharma M, Singh SM, Singh BN, Pandey A, Nguyen QD, Gupta VK. 2023. A global perspective on a new paradigm shift in bio-based meat alternatives for healthy diet. Food Res Int 169:112935.

Rajendran S, Mallikarjunan PK, O'Neill E. 2022. High pressure processing for raw meat in combination with other treatments: A review. Journal of Food Processing and Preservation 46:e16049.

Rehman N, Edkins V, Ogrinc N. 2024. Is Sustainable Consumption a Sufficient Motivator for Consumers to Adopt Meat Alternatives? A Consumer Perspective on Plant-Based, Cell-Culture-Derived, and Insect-Based Alternatives. Foods 13:1627.

Rooney D, Muller SM. 2023. Woke Sausages at the Cracker Barrel: Gastronativism and the Synecdochic Politics of Plant-Based Meat. Rhetor Public Aff 26:1-34.

Rubio NR, Xiang N, Kaplan DL. 2020. Plant-based and cell-based approaches to meat production. Nat Commun 11:1-10.

Samad A, Alam AN, Kumari S, Hossain MJ, Lee EY, Hwang YH, Joo ST. 2024. Modern Concepts of Restructured Meat Production and Market Opportunities. Food Sci Anim 44:284-298.

Samad A, Kim S, Kim CJ, Lee EY, Kumari S, Hossain MJ, Alam AN, Muazzam A, Bilal U, Hwang YH, Joo ST. 2024. Revolutionizing Cell-Based Protein: Innovations, Market Dynamics, and Future Prospects in the Cultivated Meat Industry. J Agric Food Res 101345.

Samad A, Kumari S, Hossain MJ, Alam AM, Kim SH, Kim CJ, Lee EY, Hwang YH, Joo ST. 2024. Recent Market Analysis of Plant Protein-Based Meat Alternatives and Future Prospect. J Anim Plant Sci 34:977-987.

Science Daily. 2021. Devising new meat alternatives with 3D printing — and cocoa butter. Available From: https://www.sciencedaily.com/releases/2021/12/211208090151.htm Accessed at August 1, 2024.

Sha L, Xiong YL. 2020. Plant protein-based alternatives of reconstructed meat: Science, technology, and challenges. Trends Food Sci Technol 102:51-61.

Shahid M, Shah P, Mach K, Rodgers-Hunt B, Finnigan T, Frost G, Neal B, Hadjikakou M. 2024. The environmental impact of mycoprotein-based meat alternatives compared to plant-based meat alternatives: A systematic review. Futur Foods 100410.

Shapiro P. Clean meat: 2024. How growing meat without animals will revolutionize dinner and the world. Simon and Schuster. Available From: https://books.google.co.kr/books?hl=en&lr=&id=tbwAEQAAQBAJ&oi=fnd&pg=PP9&dq=%5B81%5D+.%09Shapiro+P.+Clean+meat:+2024.+How+growing+meat+without+animals+will+revolutionize+dinner+and+the+world.+Simon+and+Schuster%3B+2024+Apr+9.&ots=ObdSQoxlcr&sig=Wldi13ubWhibxwlfZh8McMTXafw&redir_esc=y#v=onepage&q&f=false. Accessed at Aug 17, 2024

Siddiqui SA, Zannou O, Karim I, Kasmiati, Awad NM, Gołaszewski J, Heinz V, Smetana S. 2022. Avoiding food neophobia and increasing consumer acceptance of new food trends—A decade of research. Sustainability 14:10391.

Stephens N, Sexton AE, Driessen C. 2019. Making sense of making meat: key moments in the first 20 years of tissue engineering muscle to make food. Front sustain food syst 3:432585.

Stone AK, Tanaka T, Nickerson MT. 2019. Protein quality and physicochemical properties of commercial cricket and mealworm powders. J Food Sci Tech 56:3355-3363.

Sujatha GS, Teja KS, Kumar GA, Uchai P, Hema AP, Mamatha M, Ramya R, Devi DL. 2024. Harnessing the Power of Insects: A Sustainable Approach to Food and Feed Production. European j nutr food saf 16:294-308.

Szulc K. 2023. Edible insects: A study of the availability of insect-based food in Poland. Sustainability 15:14964.

Teixeira CS, Villa C, Costa J, Ferreira IM, Mafra I. 2023. Edible insects as a novel source of bioactive peptides: A systematic review. Foods 12:2026.

The Guardian. 2013. First hamburger made from lab-grown meat to be served at press conference. Available online From: https://www.theguardian.com/science/2013/aug/05/first-hamburger-lab-grown-meat-press-conference Accessed at June 11, 2024.

Treich N. 2021. Cultured meat: promises and challenges. Environ Resour Econ 79:33-61.

Van Huis A, Oonincx DG. 2017. The environmental sustainability of insects as food and feed. A review. Agron Sustain Dev 37:1-4.

Verbeke W, Spranghers T, De Clercq P, De Smet S, Sas B, Eeckhout M. 2015. Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens. Anim Feed Sci Technol 204:72-87.

Wang Y, Tuccillo F, Lampi AM, Knaapila A, Pulkkinen M, Kariluoto S, Coda R, Edelmann M, Jouppila K, Sandell M, Piironen V. 2022. Flavor challenges in extruded plant-based meat alternatives: a review. Compr Rev Food Sci Food Saf 21:2898-2929.

Woodholme Cardiovascular Associates. 2020. New Plant-Base Burger Choices. Available From: https://woodholmecardio.com/new-plant-base-burger-choices/. Accessed at June 11, 2024.

Zhang M, Zhao X, Li Y, Ye Q, Wu Y, Niu Q, Zhang Y, Fan G, Chen T, Xia J, Wu Q. 2024. Advances in serum-free media for CHO cells: From traditional serum substitutes to microbial-derived substances. Biotechnol J 19:2400251.

Zhao D, Huang L, Li H, Ren Y, Cao J, Zhang T, Liu X. 2022. Ingredients and process affect the structural quality of recombinant plant-based meat alternatives and their components. Foods 11:2202.

Zheng H, Xiong G, Han M, Deng S, Xu X, Zhou G. 2015. High pressure/thermal combinations on texture and water holding capacity of chicken batters. Innov Food Sci Emerg Technol 30:8-14.

Zimberoff L. 2021. Technically Food: Inside Silicon Valley's Mission to Change what We Eat. Abrams. Available From: https://books.google.co.kr/books?hl=en&lr=&id=YNLRDwAAQBAJ&oi=fnd&pg=PT3&dq=%5B97%5D+.%09Zimberoff+L.+Technically+Food:+Inside+Silicon+Valley%27s+Mission+to+Change+what+We+Eat.+Abrams%3B+2021+Jun+1.&ots=ZZAECBeeLD&sig=42eSubBvs0HnmY7eADEYBm4G5zk&redir_esc=y#v=onepage&q&f=false. Accessed at Aug 22, 2024

Zioga E, Tøstesen M, Madsen SK, Shetty R, Bang-Berthelsen CH. 2022. Bringing plant-based Cli-meat closer to original meat experience: insights in flavor. Futur Foods. 5:100138.

Kim CJ, Kim SH, Lee EY, Hwang YH, Lee SY, Joo ST. 2024. Effect of Chicken Age on Proliferation and Differentiation Abilities of Muscle Stem Cells and Nutritional Characteristics of Cultured Meat Tissue. Food Sci Anim Resour 44:1167-1180

Khayrova A, Lopatin S, Varlamov V. 2024. A Review on Characteristics, Extraction Methods and Applications of Renewable Insect Protein. J Renew Mater 12:923-948.

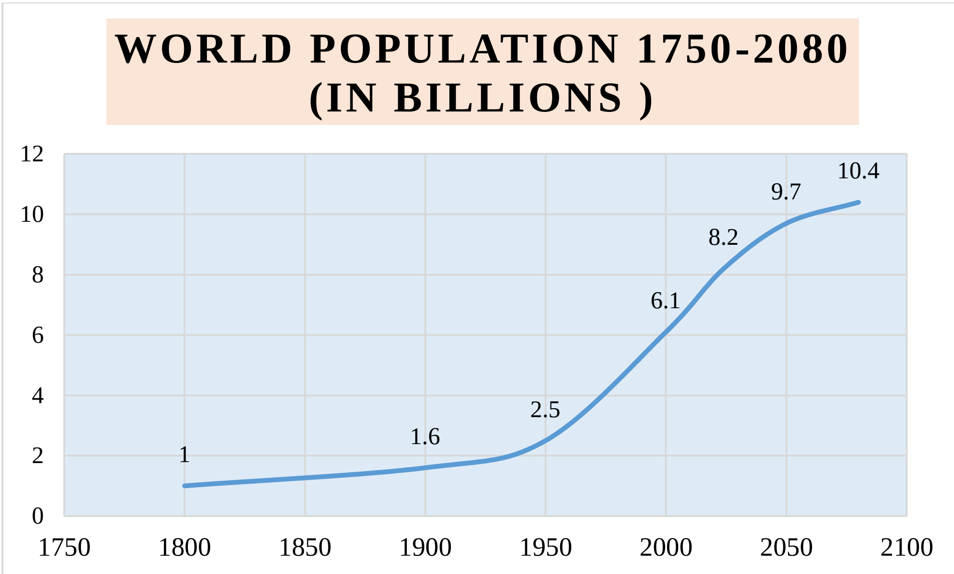


Figure 1: Trend of Increasing Population of World

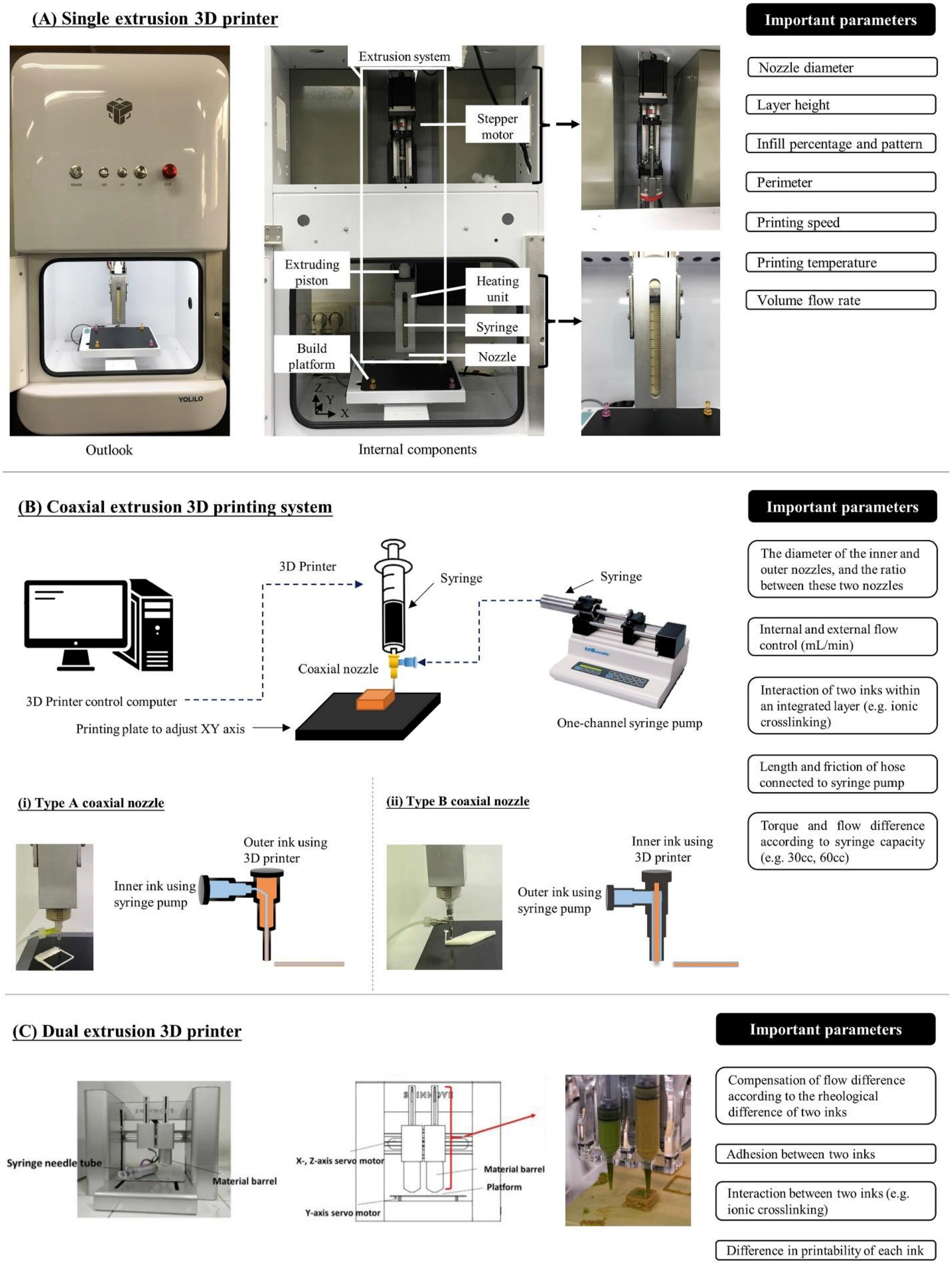

(A) Single extrusion 3D printer
Important parameters
Nozzle diameter
Layer height
Infill percentage and pattern
Perimeter
Printing speed
Printing temperature
Volume flow rate
Extrusion system
Stepper motor
Extruding piston
Heating unit
Syringe
Build platform
Nozzle
YOLILO
Outlook
Internal components
(B) Coaxial extrusion 3D printing system
Important parameters
The diameter of the inner and outer nozzles, and the ratio between these two nozzles
Internal and external flow control (mL/min)
Interaction of two inks within an integrated layer (e.g. ionic crosslinking)
Length and friction of hose connected to syringe pump
Torque and flow difference according to syringe capacity (e.g. 30cc, 60cc)
3D Printer
Syringe
Syringe
Coaxial nozzle
3D Printer control computer
Printing plate to adjust XY axis
One-channel syringe pump
(i) Type A coaxial nozzle
Outer ink using 3D printer
Inner ink using syringe pump
(ii) Type B coaxial nozzle
Inner ink using 3D printer
Outer ink using syringe pump
(C) Dual extrusion 3D printer
Important parameters
Compensation of flow difference according to the rheological difference of two inks
Adhesion between two inks
Interaction between two inks (e.g. ionic crosslinking)
Difference in printability of each ink
Syringe needle tube
Material barrel
X-, Z-axis servo motor
Material barrel
Platform
Y-axis servo motor

Figure 2: 3D Bioprinting process in Plant-based Meat alternatives (Figure reused with the permission of Elsevier License ID 5862930718225)

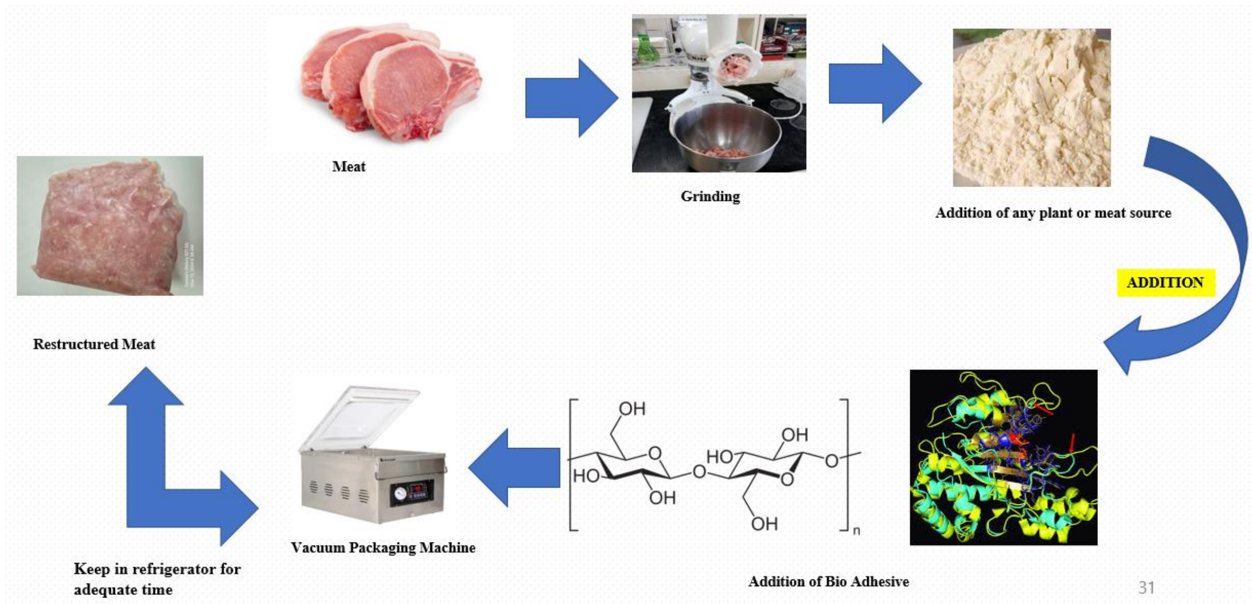


Figure 3: Process of manufacturing Restructured meat

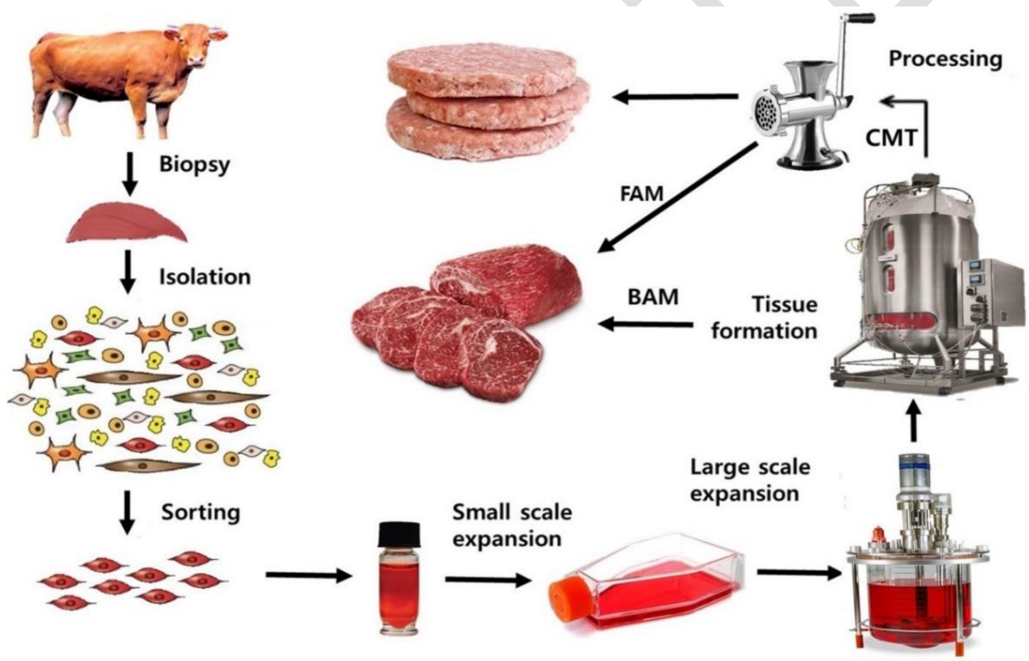


Figure 4. Process of cultured meat production (Reused with permission of Joo et al)

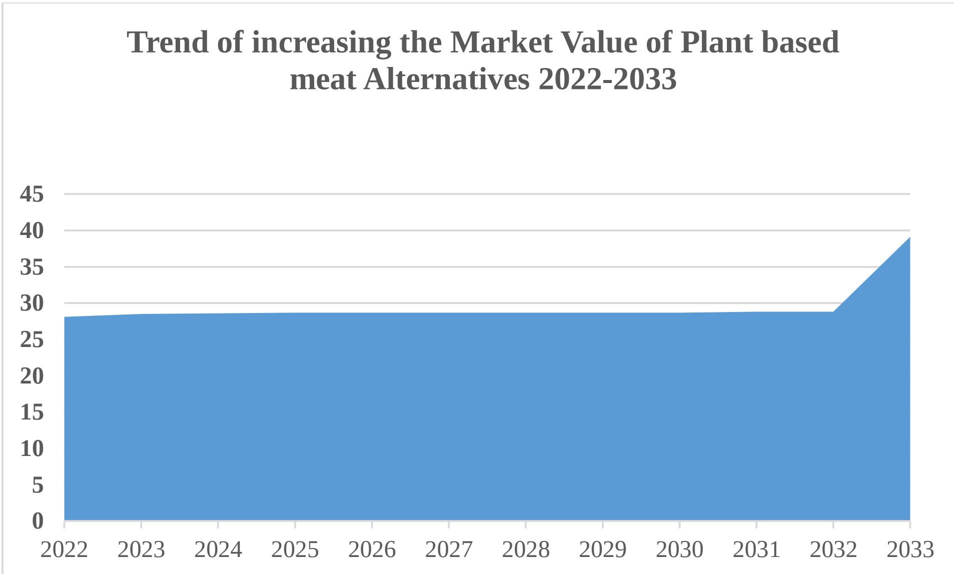


Figure 5: Trend of Plant-based meat alternative market

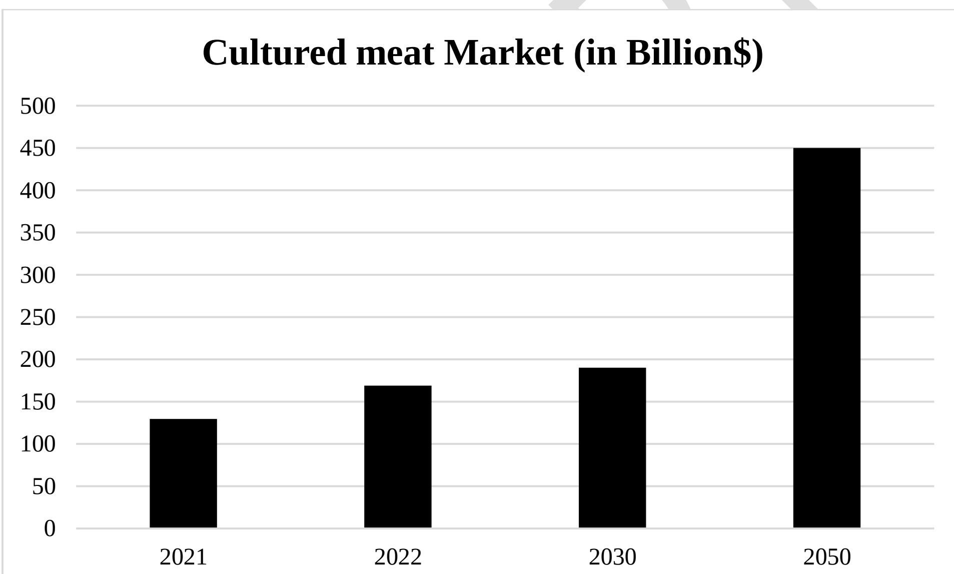


Figure 6: Market scenario of cultured meat

Table 1: Development of new technologies and innovations in the sector of Plant-based meat alternatives

Development Area	Description	Reference
3D Printing	Researchers have developed plant-based meat alternatives using 3D printing technology. Ingredients like soy and wheat proteins, along with cocoa butter, are used to create a meat "dough" that can be effectively printed and retains its shape after printing. Figure 2 explains the process of 3D bioprinting in plant-based meat alternatives more clearly.	(Science Daily, 2021)
Protein Spinning	Fiber-spinning technology is being optimized to develop plant-based meat analogs. This involves extruding fine fibers from soy protein and polysaccharides, which are then assembled into structures resembling muscle fibers.	(Kumari et al., 2024)
Plant Protein Materials	Studies are exploring various plant proteins (e.g., lentils, soybeans, peas, buckwheat) for 3D printing to meet the growing demand for meat alternatives.	(Auyeskhan et al., 2024)
Innovative Textures	Companies like Alt Farm are using patented nozzle designs in 3D printing to recreate specific textures in plant-based meats, enhancing their resemblance to real meat.	(Print.com, 2021)

Fermentation	Companies are using fermentation to enhance the flavor and texture of plant-based meats. This process involves using microorganisms to break down plant proteins, creating a more meat-like taste and texture.	(Zioga et al., 2022)
Cellular Agriculture	Some companies are combining plant-based ingredients with cultured animal cells to create hybrid products that offer the taste and texture of real meat with the sustainability of plant-based ingredients.	(Rubio et al., 2020)
High-Moisture Extrusion	This technique is used to create fibrous, meat-like textures from plant proteins. It involves heating and shearing plant proteins under high moisture conditions to align the protein fibers, mimicking the texture of meat.	(Guyony et al., 2023)
Flavor Enhancements	Advances in flavor technology are helping to close the gap between plant-based and animal-based meats. Natural flavors and aroma compounds are being developed to replicate the taste of beef, chicken, and pork.	(Liu et al., 2023)
Nutritional Improvements	Efforts are being made to enhance the nutritional profile of plant-based meats by fortifying them with vitamins, minerals, and other nutrients to match or exceed the nutritional content of animal-based meats.	(McClements && McClements, 2023)
Mycoprotein Development	Mycoprotein, derived from fungi, is being developed as a sustainable and nutritious meat alternative. It	(Molfetta et al., 2022)

	offers a meat-like texture and is rich in protein and fiber.

Table 2: Recent Development in Restructured Meat

Development	Description	Reference
Hot-Set Gels	It uses thermal processes to form gels that bind small meat pieces together, enhancing texture and appearance.	(Zheng et Al., 2015)
Cold-Set Gels	Utilizing chemical reactions to bind meat pieces without heat, preserving more nutrients and flavors.	(Gómez et al., 2020)
High-Pressure Processing (HPP)	Applying high pressure to bind meat pieces improves texture and reduces microbial load.	(Rajendran et al., 2022)
Alternative Protein Integration	Incorporating plant-based proteins into restructured meat to reduce meat content and environmental impact.	(Sha et al., 2020)
Enhanced Sensory Attributes	Improving the taste, texture, and appearance of restructured meat products to make them more appealing to consumers.	(Gadekar et al., 2015)

Table 3: Recent Trends in Cultured Meat Production

Advancements in Cultured Meat Production	Description	References
Fused Deposition Modeling (FDM)	This strategy is used to make a framework using thermoplastic biomaterials.	(Lee & Choi, 2024)
Stereolithography (SLA)	Stereolithography (SLA) is a cost-effective approach that assists in the fast manufacturing of prototypes.	(Kafle et al., 2021)
Selective Laser Sintering	This 3D printing strategy fuses or binds small charged materials together by using powerful lasers which create a solid arrangement.	(Han et al., 2022)
Biomimetic Scaffolds	This approach presents a novel strategy for 3-dimensional cell culture approaches that could be utilized in tissue engineering.	(Badekila et al., 2021)
Cultured fat	Fats which are cultured in the lab using adipose tissues	(Liu et al., 2023)
Soft Bioreactors	The bioreactor can refine the rate of production	(Dvorak et al., 2024)
Serum-Free Media	Such media contains a nutritional formulation that needs cells for their progress and is free of any animal-based serum.	(Zhang et al., 2024)

Table 4: Recent trends in insect-based Protein alternatives

Development	Description	Reference
Bioactive Peptides from Insects	Researchers are exploring the use of insect proteins as substrates to obtain bioactive peptides, which have potential health benefits.	(Teixeira et al., 2023)
Insect Protein as Bio-Converters	Insects are being studied for their ability to convert various grades of waste into food or feed proteins, offering an efficient and sustainable protein source.	(Piercy et al., 2023)
Insect-Based Protein Startups	Several startups are leading the industry by developing innovative insect-based protein products for human consumption and animal feed.	(Grasso & Bordiga, 2023)
Consumer Acceptance Studies	Studies are being conducted to understand and improve consumer acceptance of insect-based proteins, focusing on overcoming cultural barriers and food neophobia.	(Szulc, 2023)
Nutritional and Environmental Benefits	Insect proteins are recognized for their high nutritional value and low environmental impact, making them a sustainable alternative to traditional livestock proteins.	(Gascoet al., 2020)

Table 5: Market trends of restructured meat

Aspect	**Value**	**Source**
Global Market Size (2023)	$4.6 billion	(Rai et al., 2023)
Key Regions	North America, Europe, Asia-Pacific	(Samad et al., 2024b)
Top Companies	Tyson Foods, Cargill, JBS	(Howard et al., 2019)
Consumer Preferences	Low-fat, low-salt, high-fiber	(Campagnol et al., 2023)
Environmental Impact	Reduction in waste, sustainable production	(Pintado & Delgado-Pando, 2020)

Table 6: Comparison of different meat alternatives

Aspect	Plant-Based Meat	Restructured Meat	Cultured Meat	Insect-Based Meat
Market Value	$6.1 billion in 2022 (Caputo et al., 2024)	Growing due to advancements in food technology (Samad et al., 2024b)	An emerging market with high growth potential (Chodkowska et al., 2022)	Expected to grow with increasing awareness (Malila et al., 2024
Consumer Acceptance	High, but needs improvement in taste and affordability (Gradl et al., 2024)	Increasing due to health and sustainability benefits (Samad et al., 2024b)	Gradually growing, but faces perception and cost challenges (Samad et al., 2024c)	Low, but improving with awareness and innovative products (Malila et al., 2024)
Production Cost	Relatively low and decreasing (Samad et al., 2024a)	Moderate, depending on the technology and ingredients	High, but expected to decrease with scale (Niszczota & Błaszczyński, 2024)	Low, but varies with the type of insect and processing method (Khayrova et al., 2024)

		used (Molina et al., 2024)		
Environmental Impact	Lower than conventional meat but varies by product (Bakhsh et al., 2021a)	Lower than traditional meat, depends on ingredients (Molina et al., 2024)	Significantly lower than conventional meat (Chodkowska et al., 2022)	Very low insects require less land, water, and feed (Malila et al., 2024)
Nutritional Value	High in protein, fiber, and other nutrients, but varies by product (Kumari et al., 2023)	It can be tailored to match or exceed conventional meat (Samad et al., 2024b)	Comparable to traditional meat, it can be customized (Chodkowska et al., 2022)	High in protein, vitamins, and minerals (Khayrova et al., 2024)
Regulatory Status	Widely accepted and regulated (Kumari et al., 2023)	Accepted, but varies by region (Samad et al., 2024b)	Limited, but increasing with more approvals (Samad et al., 2024c)	Limited, varies by region, but gaining acceptance (Malila et al., 2024)
Key Players	Beyond Meat, Impossible Foods (Samad et al., 2024a)	Various food tech companies	Memphis Meats, Mosa Meat (Samad et al., 2024c)	Aspire Food Group, Entomo Farms (Megido et al., 2024)

(Molina et al.,

2024)

Table 7: Challenges and Opportunities in Meat Alternative Sector

Challenges	Opportunities
Consumer Acceptance: Taste and Texture: Many consumers still prefer the taste and texture of traditional meat (Giezenaar et al., 2024) Perception: Some consumers view meat alternatives as overly processed or unnatural (Ford et al., 2024)	**Environmental Benefits:** Sustainability: Meat alternatives generally have a lower environmental footprint compared to traditional meat (Samad et al., 2024a). Resource Efficiency: Producing plant-based and cultured meat uses fewer resources like water and land (Samad et al., 2024c).
Supply Chain Issues Ingredient Sourcing: Ensuring a consistent supply of high-quality ingredients can be difficult (Zhao et al., 2022) Distribution: Efficiently distributing perishable products globally poses logistical challenges (Zhao et al., 2022).	**Health Benefits:** Nutritional Advantages: Many meat alternatives offer health benefits, such as lower cholesterol and fat content (Bakhsh et al., 2021a). Dietary Preferences: They cater to various dietary needs, including vegetarian, vegan, and flexitarian diets (Bakhsh et al., 2021a).
Production Costs: High Costs: Producing cultured meat and high-quality plant-based meat can be expensive (Samad et al., 2024c)	**Technological Advancements:** Innovation: Advances in biotechnology and food science are continuously improving the taste, texture, and nutritional profile of meat alternatives (Samad et al., 2024c)

Scaling Up: Scaling production to meet global demand while maintaining quality is challenging (Samad et al., 2024c)	New Products: Ongoing research is leading to the development of new and improved products (Samad et al., 2024c)
Regulatory Hurdles: Approval Processes: Gaining regulatory approval for new products, especially cultured meat, can be lengthy and complex (Martins et al., 2024) Labeling: There are ongoing debates about how meat alternatives should be labeled.	**Market Growth:** Increasing Demand: There is growing consumer interest in sustainable and ethical food options (Bakhsh et al., 2021a). Investment: Significant investments are being made in the sector, driving innovation and expansion (Samad et al., 2024c)