Food Science of Animal Resources

Food Sci. Anim. Resour. 2024 January 44(1):39~50
DOI https://doi.org/10.5851/kosfa.2023.e76

pISSN : 2636-0772 eISSN : 2636-0780
http://www.kosfaj.org

REVIEW

Trends in Hybrid Cultured Meat Manufacturing Technology to Improve Sensory Characteristics

AMM Nurul Alam[1], Chan-Jin Kim[1], So-Hee Kim[1], Swati Kumari[1], Seung-Yun Lee[2], Young-Hwa Hwang[3], and Seon-Tea Joo[1,2,3,*]

[1]Division of Applied Life Science (BK21 Four), Gyeongsang National University, Jinju 52828, Korea
[2]Division of Animal Science, Gyeongsang National University, Jinju 52828, Korea
[3]Institute of Agriculture & Life Science, Gyeongsang National University, Jinju 52828, Korea

OPEN ACCESS

Received October 3, 2023
Revised October 26, 2023
Accepted November 20, 2023

***Corresponding author** : Seon-Tea Joo
Division of Applied Life Science (BK21 Four), Gyeongsang National University, Jinju 52828, Korea
Tel: +82-55-772-1943
Fax: +82-55-772-1949
E-mail: stjoo@gnu.ac.kr

***ORCID**
AMM Nurul Alam
https://orcid.org/0000-0003-3153-3718
Chan-Jin Kim
https://orcid.org/0000-0001-5020-6873
So-Hee Kim
https://orcid.org/0000-0003-3966-6160
Swati Kumari
https://orcid.org/0000-0002-9929-6758
Seung-Yun Lee
https://orcid.org/0000-0002-8861-6517
Young-Hwa Hwang
https://orcid.org/0000-0003-3687-3535
Seon-Tea Joo
https://orcid.org/0000-0002-5483-2828

Abstract The projected growth of global meat production over the next decade is attributed to rising income levels and population expansion. One potentially more pragmatic approach to mitigating the adverse externalities associated with meat production involves implementing alterations to the production process, such as transitioning to cultured meat, hybrid cultured meat, and meat alternatives. Cultured meat (CM) is derived from animal stem cells and undergoes a growth and division process that closely resembles the natural *in vivo* cellular development. CM is emerging as a widely embraced substitute for traditional protein sources, with the potential to alleviate the future strain on animal-derived meat production. To date, the primary emphasis of cultured meat research and production has predominantly been around the ecological advantages and ethical considerations pertaining to animal welfare. However, there exists substantial study potential in exploring consumer preferences with respect to the texture, color, cuts, and sustainable methodologies associated with cultured meat. The potential augmentation of cultured meat's acceptance could be facilitated through the advancement of a wider range of cuts to mimic real muscle fibers. This review examines the prospective commercial trends of hybrid cultured meat. Subsequently, the present state of research pertaining to the advancement of scaffolding, coloration, and muscle fiber development in hybrid cultured meat, encompassing plant-based alternatives designed to emulate authentic meat, has been deliberated. However, this discussion highlights the obstacles that have arisen in current procedures and proposes future research directions for the development of sustainable cultured meat and meat alternatives, such as plant-based meat production.

Keywords cultured meat, alternative protein, hybrid cultured meat, scaffolding

Introduction

According to the OECD and FAO (2021), it is anticipated that the consumption of meat proteins worldwide will experience a 14% rise over the next decade, mostly driven by escalating income levels and population expansion. This projection is in

© KoSFA. This is an open access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licences/by-nc/3.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

comparison to the average consumption levels observed between 2018 and 2020. The escalating demand is intricately linked to a range of issues, encompassing public health and environmental challenges, as well as concerns over animal care and ethical considerations. It is anticipated that the rise in global meat production would lead to a significant increase in greenhouse gas emissions (FAO, 2014), as well as water pollution, diminished access to fresh water, and adverse alterations in biodiversity, all of which pose a direct threat stemming from the expanding livestock sector (Steinfeld et al., 2006). According to Sarlio (2018), the utilization of calories by animals for maintenance and non-edible tissue creation is estimated to be approximately 97%, which is widely regarded as inefficient. The consumption of meat especially red meat in excessive amounts has been found to pose health hazards for individuals (Abu-Ghazaleh et al., 2021). Nevertheless, cultured meat (CM) from live animal cells may fit the consumer demand for growing real meat consumption (Ismail et al., 2020).

CM is produced from live animal cell cultures and is considered an alternative to real meat (Post, 2014). CM approach acquired a larger concentration globally in the research arena, media, investors, specific groups of consumers, and animal welfare organizations (Goodwin and Shoulders, 2013; Schneider, 2013; Stephens et al., 2018; Verbeke et al., 2015). A great number of efforts are ongoing to produce CM to mimic real meat from beef, poultry, pork, and seafood by researchers. The so-called hybrid CM (HCM) is a hybridization of animal cells and possible ingredients from plants, bacteria, and algae including various types of binders to mimic the real meat taste and texture of real meat (Lee et al., 2023). Hybrid meat products represent a novel category of goods wherein a portion of the meat content, often around 20%, is substituted with alternative protein sources, including plant-based alternatives (Baune et al., 2023). According to existing research, these products have the potential to function as a viable option for a particular demographic seeking to reduce their meat consumption, therefore aiding in the transition towards a diet that is both healthier and more environmentally sustainable.

CM is expected to be safer in terms of public health (Willett et al., 2019) and a way out toward a sustainable way to produce food with high-quality protein and theorized to be able to produce 1 billion beef burgers from a single cow biopsy (Kumar, 2021). The first-ever regulatory approval for CM production was for “Eat Just” in 2020 in Singapore (GFI, 2020). Upside Food and GOOD Meat got final approval from the FDA and USDA for marketing and selling cultured chicken meat products in 2023 (GFI, 2023). CM still possesses major challenges in terms of high production cost, product quality, and consumer embracing (GFI, 2023). Numerous developments need to be addressed to make CM mimic real meat e.g., myoglobin production, marbling of the meat, culture media optimization, sustainable production techniques, muscle bundle formation to mimic different meat cuts, major sensory attributes, nutritional values, and scaffolding technology (Levi et al., 2022), etc.

Several commercial manufacturers ventured into plant-based meat (PBM) market and few stand out as pacesetters e.g., Beyond Meat, Impossible Foods, Eat Just, Memphis Meats, Aleph Farms, Mosa Meat, Cultured Decadence, and BlueNalu (GFI, 2023). These companies advance toward sustainability in manufacturing HCM, including PBM, through production capacity, product quality, legislation, and research and development based on consumer demand. In this regard, this paper reviews the opportunity of HCM or meat alternatives and the advanced challenges related to the structural and sensory characteristics to focus the consumer sustainability.

Commercial Prospect of Cultured Meat

According to the Good Food Institute, the Overall value of CM in 2022 is estimated at USD 0.3 Billion and is expected to grow to USD 20 Billion in 2023 with a growth rate of 143% (GFI, 2023). Health safety, environmental pollution, and vegan movement issues trigger a driving force to alternative meat solutions both by the industry and the consumers. Table 1

Table 1. A list of companies focused on the development and production of cultured meat, plant based meat, technological advancements, and support supplies

Company	Focus	Present phase	Year founded	Animal-type/analog	Country
Aleph Farms	Cultivated beef steak	Production	2017	Beef/veal	Israel
BioTech Foods	Cultivated meat products	Production	2017	Beef/veal	Spain
BioBQ	Cultivated beef brisket and jerky	Production	2018	Beef/veal	United States
Gaia Foods	Cultivated meat products	Production	2019	Beef/veal	Singapore
GOURMEY - Suprême SAS	Restaurant-grade meats directly from animal cells	Production	2019	Duck	France
Ivy Farm Technologies	Cultivated pork products.	Production	2019	Pork	United Kingdom
Lab Farm Foods	Cultivated meats, including pork and chicken nuggets	Production	2019	Pork/chicken	United States
Alife Foods	Cultured schnitzel (special meat cut)	Production	2019	Beef/veal	Germany
Steakholder Foods	3D printed cultivated meat	Production	2019	Beef/veal	Israel
Mirai Foods AG (fmr. AlphaMeats)	Cultivated meat products	Production	2019	Beef/veal	Switzerland
Blue Ridge Bantam	Hybrid alternative poultry products	Production	2020	Chicken	United States
Novel Farms	Whole cuts of cultured Iberian pork	Production	2020	Pork	United States
Ohayo Vallley	Plant-based and cultivated meat to produce cultivated wagyu ribeye	Production	2020	Beef/veal	United States
Magic Valley	Cultivated lamb meat	Production	2021	Mutton/lamb	Australia
Ambi Real Food	Cultured beef based meat products	Production	2021	Beef/veal	Brazil
LiquiBio	Edible scaffolding	Production	2022	Beef/chicken/pork/turkey/ duck/mutton/goat	United Kingdom
Joes Future Food / Nanjing Zhouzi	Serum-free culture media	Research	2019	Pork/beef/veal	Mainland China
Meat.The End	Techniques and ingredients to boost the texture of meat alternatives	Research	2020	Chicken/beef/veal	Israel
SuperMeat	Cultivated chicken	Development	2015	Chicken	Israel
Appleton Meats	Clean ground beef, chicken	Development	2016	Beef/veal/chicken	Canada
Uncommon	Cultivated meat	Development	2018	Beef/veal	United Kingdom
Mission Barns	Cultivated meat (Kosher Bacon)	Development	2018	Pork	United States
SciFi Foods	Cultivated and cultured meat products	Development	2019	Beef/veal	United States
WildBio (Formerly Mogale Meats)	Cell-lines for cultured meat	Development	2020	Beef/veal	South Africa
Ants Innovate	Cultivated whole meat cuts	Development	2020	Pork	Singapore
Re:meat	Large-scale production of cultivated meat	Development	2022	Beef/veal	Sweden
MyriaMeat	100% real meat muscle	Development	2022	Beef/veal/pork	Germany
Foodurama	Plant-based and cell-cultured meat.	Development	2022	Beef/veal/chicken/ mutton/lamb	Indonesia

Data modified from GFI (2023).

indicates an immense opportunity for this sector in the future (GFI, 2023). There are 28 companies working on meat-based products, out of which sixteen are involved in the production of CM or plant-based analogs and scaffolding. There is one research-based company working on serum-free culture media and the other one on techniques and ingredients to boost the texture of meat alternatives. Nine companies are in the development phase for the production of CM and meat alternatives and one is involved in the development of a cell line for CM.

In recent days the intensified interest of consumers in PBM products and CM is an outcome of continuous product development and marketing efforts. The conception of any new invention always has some drawbacks and, in this case, there are challenges from consumers and technological barriers (Sanchez-Sabate and Sabaté, 2019) especially on meat color, texture, taste, etc. as real meat and emphasized by researchers for future improvements (Bakhsh et al., 2021, Bakhsh et al., 2022; Weinrich, 2019). By embracing and developing various sorts of reorganizational technology, such as 3D scaffolding, PBM and CM may be able to deliver safer and more environmentally friendly state products. So far plant and animal-based CM found to be safe and could be ideal alternatives to address the growing need for animal protein with the growing global population (Zhang et al., 2022). In the parts that follow, an explanation will be given of the technological characteristics that might offer solutions to the problems in Human Capital Management. This is done with the intention of generating the need for additional research.

Sensory Characteristics of Hybrid Cultured Meat

Processing of different functional ingredients turns into a brand-new appearance with consistent nutritional characteristics known as ‘Restructured food’ (Polášek et al., 2021). Various food additives are included to develop compounded structured food (Carpentieri et al., 2022). Structured meat is a type of reconstituted food that is attaining admiration from consumers as a substitute for orthodox meat products. HCM is a kind of structured food that reassembles animal-based CM with PBM to create a new texture and appearance that mimics real meat. Structured meat like HCM is considered to be safe, healthy to consume, and capable of solving animal welfare issues. However, in order to gain a preference that can meet consumer expectations, HCMs containing PBM will have to have sensory characteristics similar to those of natural meat (Bakhsh et al., 2022). The texture, color, taste, etc. would be the major criteria in marketing this kind of cell-based CM in the future (Joo et al., 2022). In addition to these sensory characteristics, consumers will also be increasingly interested in nutrition. The development processes employed in controlled atmosphere packaging are intricately linked to the structural composition of muscle tissue, as the shape of muscles is directly associated with the nutritional and sensory attributes of meat. Satellite cells are predominantly obtained from the skeletal muscles of several animal species, including cattle, chicken, swine, lamb, and fish, in contemporary methodologies. The fibrous texture commonly observed in red meat, such as beef, can be attributed to the intricate hierarchical tissue organization. The muscle fiber serves as the fundamental functional component, encompassed by connective tissue, intramuscular fat, vascular, and nerve tissues. According to Listrat et al. (2016), the key factors that influence muscle texture and quality characteristics are muscle fibers, fat, and connective tissue. HCM products have the advantage of being able to produce customized nutritional products for consumer needs. In this regard, research on the development of HCM products focused on the nutritional and structural development of meat that meets consumer needs will present immense opportunities for CM market in the near future.

To effectively design HCM products that align with customer demands, it is imperative to do research on plant proteins that constitute a substantial proportion of HCM and/or PBMs produced using these proteins. While the PBM sector is experiencing growth in the market, it is important to consider that negative sensory feedback from customers has the potential to restrict its market expansion. The texture and sensory attributes of PBM are not on par with those of actual meat, as the fibrous structure of meat plays a vital role in this regard (Lee et al., 2023). The inclusion of hydrocolloids is known for their potential to improve the textural properties of PBM. Hydrocolloids could be precious for the development of PBM to improve texture and sensory characteristics. The myofibrillar protein, which primarily comprises myosin and actin, is crucial in the development of the desired texture and water-holding capacity of comminuted beef products. High Acyl gellan gum was shown to produce large fibers when PBM containing soy protein isolate (SPI; Taghian Dinani et al., 2023). Positive feedback was revealed from the addition of wheat gluten on the texture, binding properties, moisture retention, and sensory attributes in PBM (Chiang et al., 2021). But as an allergen wheat gluten is not accepted by consumers with enteric problems (Theethira and Dennis, 2015).

Meanwhile, edible cell microcarriers can be directly added to the final HCM product, which may reduce the cost and yield losses (Nienow et al., 2014). Edible cell carriers like Chitosan-collagen (90:10) were successfully produced to culture from different primary livestock animal cells and have considerable potential for the development of CM products when incorporated these carriers can contribute to the CM sensorial and nutritional values (Zernov et al., 2022).

Plant Proteins Used in Manufacture of Hybrid Cultured Meat and/or Plant-Based Meat

The obstacles encountered in the development of PBM substitutes revolves around the replication of tactile characteristics inherent in meat-based products, such as mouthfeel, chewiness, cohesiveness, and springiness. Nevertheless, the development of desired characteristics in food products relies on the interplay between the selected protein(s) and/or non-protein components, as well as the utilization of sophisticated and innovative techniques, owing to the inherent disparities in the structural chemistry of plant and meat proteins (Mattice and Marangoni, 2020).Various plant proteins, including those found in cereals, legumes, pulses, and leaves, can be used to make plant meat alternatives (Lee et al., 2023). Commonly wheat, corn, rice, barley, sorghum, and amaranth grain are sources of cereal proteins. Moreover soybeans, rapeseed/canola, sunflower seeds, sesame, flaxseeds, and linseeds are sources of oil-seed proteins (Kyriakopoulou et al., 2019).

Soy protein, specifically in the forms of SPI, soy protein concentrate (SPC), and soy flour, serves as the primary plant-based protein utilized in the production of PBM and/or HCM. Soy proteins have a wide range of functional qualities, including hydrophilicity, lipophilicity, emulsifying capabilities, and the capacity to create gel structures. In order to produce artificial meat substitutes, SPC and soy protein are frequently employed and they play an important role in reducing product cost and making it competitive in the market (Bakhsh et al., 2022).

The extraction process demonstrates that SPI possesses a comparative advantage over SPC in terms of protein content. Various approaches were employed for protein extraction in the case of each product. An alcohol extraction is used to collect SPC where it retains about 70% of its protein content (Lee et al., 2023). On the other hand, protein retention is 90% in the case of SPI. An alkaline extraction and leached at an acidic pH assisted in having 90% of its protein content. SPI is well accepted in the industry and research arena for the production of meat analogues due to its brighter color and a drearier flavor than other soy-sourced ingredients (Kyriakopoulou et al., 2019). The end products of SPI possess a meat-like texture after hydration and are much more economical than the other plant protein sources (Sun et al., 2021). The physiological and nutritional characteristics of soy protein have been found to surpass those of actual meat. Meat mimics created employing soy-derived proteins exhibit a larger protein content compared to authentic meat, and furthermore, they possess elevated nutritional properties. Moreover, it has been demonstrated that the fat and cholesterol levels in plant-based alternatives are comparatively lower when compared to those found in traditional meat sources (Cavallini et al., 2006).

Wheat gluten, which forms thin proteins on elongations and may be swiftly converted into a fibrous protein, is another often used grain protein. Wheat gluten used as a scaffolding material in the development of meat analogues in its 3D network form. Wheat protein is known for its, which helps provide the most commonly encountered form of consistent meat analogues. Additionally, to create meat extenders, wheat gluten can be combined with soy flour or SPI (Asgar et al., 2010). The allergens in wheat gluten should be taken into account while using in the production of meat analougues, as these could be problematic for children (regular and with special need) and sensitive consumers (Keet et al., 2009; Martínez-Villaluenga et al., 2008). Nevertheless, due to its water insolubility, wheat gluten cannot be used extensively in the food processing industry (Asgar et al., 2010).

Legumes are widely recognized for their high-quality and abundant protein content. Legume protein sources encompass a variety of plant-based foods, including beans, chickpeas, lentils, lupines, and peas. Legume-based proteins have a notably abundant amino acid composition in comparison to alternative plant sources. They are rich in lysine and threonine, but in comparison to cereal grain-based proteins methionine, cysteine, and tryptophan are shallow (Kurek et al., 2022). Emulsification, gelation, and foam stability are three functional characteristics exhibited by legume proteins, which enhance the efficacy of using plant protein products as food additives. Emulsification, gel formation, and foam stabilization are three functional traits of legume proteins that improve the utilization of plant protein products as food additives (Ettoumi et al., 2016). High-moisture extrusion has been used to create materials with a fibrous morphology from pea protein isolate and wheat gluten (Schreuders et al., 2019). SPI, SPC, and other plant proteins derived from soybeans are often used ingredients in the production of PBM. The identification and incorporation of alternative sources of plant-based proteins is of utmost importance. Furthermore, apart from using single ingredients, the combined effect of one or more ingredients is necessary to produce significant combinations suitable for commercial production, economic feasibility, and overall sustainability (Bakhsh et al., 2022). The primary issues associated with plant-based proteins pertain to their eating quality, specifically their capacity to effectively replicate the appearance, texture, flavor, taste, and nutritional composition of actual meat products. Furthermore, it is imperative that the product possesses the capacity to be manipulated in a manner akin to uncooked meat, and then prepared in a manner resembling meat cooking techniques, resulting in a final product that elicits a sensory encounter like to the consumption of meat. Despite advancements in the enhancement of texture and flavor in PBM alternatives, there remain obstacles in delivering a satisfactory sensory encounter and enhancing the nutritional value of such products.

Improvement of Sensory Characteristics

Improving the meat color

In natural meat, the presence of myoglobin is what gives it its distinctive red hue; in CM, on the other hand, myoglobin is not present, which results in a more pale appearance. Myoglobin expression is extinguished at ambient oxygen conditions (Gholobova et al., 2018; Lee et al., 2022; Thorrez et al., 2006). A number of initiatives guided way out to increase the myoglobin content in CM or PBM (Fraeye et al., 2020), summarized in Table 2.

Improving marbling

Consumer preference starts with the optical inspection of a product and has immense importance in meeting their expectation, especially for novel foods (Moore et al., 2021; Post and Hocquette, 2017; Post et al., 2020). The presence of marbling patterns in meat is known to increase consumer acceptance when purchasing (Lo Surdo et al., 2013). This can be

Table 2. Summary of observations from recent research on developing plant based or tissue culture meat color and concerns to trigger future research

Present observations	Future research needs
Low oxygen ambience may increase myoglobin expression during culturing muscle fibers (Post and Hocquette, 2017; Simsa et al., 2019).	Need further evaluation to assess the impact of low oxygen conditions on cultured meat (Kanatous et al., 2009; Schlater et al., 2014).
Hypoxic conditions resulted better efficiency with increased glucose uptake and lactic acid production and lipids or acetic acid media showed stimulation of myoglobin expression (Moritz et al., 2015).	Need further evaluation to assess the impact of low oxygen conditions on cultured meat (Kanatous et al., 2009; Schlater et al., 2014). Possible acidification may damage the cells (Kadim et al., 2015).
Sufficient iron is mandatory in the cell for myoglobin synthesis and color development (Rubio et al., 2019).	Uptake is transferrin-dependent (Kadim et al., 2015).
Myoglobin content in cultured meat may be improved by direct inclusion of myoglobin, recently addition of metmyoglobin (the oxidized form of myoglobin) increased cell proliferation and the content of myoglobin in cells (Simsa et al., 2019).	Bioavailability of iron and inclusion limit into myoglobin needs to be studied (Simsa et al., 2019). Still, the color of cultured beef meat is pale than real beef after adding metmyoglobin.
The possibilities of artificial color or plant-derived colors are under observation but only for processed meat products. Soy leghemoglobin was able to give the color and taste of a real beef burger (Watson, 2019).	As red meat is associated with health concerns, it is wise to develop alternative colorants for cultured meat (Gamage et al., 2018).

achieved by mimicking the marbling patterns found in traditional meat. By incorporating fat cells alongside muscle cells, cell-based meats can develop marbling patterns that enhance their visual appeal. Additionally, advanced 3D printing technologies can be utilized to create intricate structures that resemble marbling patterns, further improving the visual appearance of cell-based meats (Ong et al., 2021). To create a well-integrated structured CM that replicates the texture of conventional meat, the engineered adipose tissue was integrated within engineered bovine muscle tissue using a gentle stitching process that allowed the co-culture of the integrated construct while preserving the delicate mature adipocytes (Zagury et al., 2022). Marbling and three-dimensional type superior structure in CM yet not established in current culture techniques (Datar and Betti, 2010; Jurie et al., 2007).

Improving structure by scaffolding

The process of CM creation necessitates the utilization of satellite cells derived from live animal muscle, which are subsequently deposited onto a biomaterial substrate commonly referred to as a scaffold, microcarrier, or film. This foundation stimulates the proliferation of satellite cells in order to increase their population size. Following this, the progression of muscle fibers and adipose tissue formation persists through the process of differentiation, with the ultimate objective being the replication of the authentic structure of meat (Ostrovidov et al., 2014).

In the field of CM, it is of utmost importance to ensure the appropriate arrangement of fiber bundles in order to accurately replicate the structural characteristics observed in conventional meat. The attainment of well-organized meat can be accomplished through the utilization of scaffolds, which provide cells with an extracellular matrix-like framework for the purposes of support, differentiation, and proliferation. Different strategies are in use for scaffolding e.g., microcarriers, porous scaffolds, fiber scaffolds, hydrogels, 3D printing, scaffold-free approaches, etc., and synthetic polymers, self-assembling peptides, ECM molecules, plant & fungus derives materials are commonly used scaffolding materials (Bomkamp et al., 2022). There are four key aspects that need to be taken into account for tissue engineering (TE), of which the mechanisms are similar to scaffolds being used for CM production. Biocompatibility, biodegradability, the architecture of the scaffold, and the technology used to manufacture the scaffold are the four important areas that need to be addressed during the production of CM through TE (Seah et al., 2022). Micro carriers found to significantly increase the efficiency of cell proliferation and differentiation and it's achieved by expanding the surface area and serving anchorage-dependent cells a link (de Jong, 2023). The properties of scaffolding such as microcarriers have often been inspired by the field of TE, which needs to be adapted for CM (Singh et al., 2023).

Scaffolds that are frequently employed has the ability to be utilized in the production of human cardiac muscle because to their edible nature or their rapid biodegradation during the phases of differentiation and maturation. The utilization and advancement of edible scaffolds have the potential to decrease the expenses associated with the production process of HCM, as these scaffolds can be commercialized as a product. According to Ng and Kurisawa (2021), if edible scaffolds are to be retained in the final product, it is imperative that they are both harmless and safe for consumption, without altering the flavor or texture. Further investigation is necessary to explore sustainable, efficient, viable, and ultimately consumable polymers for implementation in the CM sector.

Conclusion

The allocation of investments and the level of interest exhibited by investors in this particular industry may serve as a promising indicator for the prospective expansion of CM and meat alternatives in the future. Consumer interest in meat alternatives, such as CM, may experience a decline unless their prices become comparable to that of actual meat. The primary research and industrialization objective should revolve around replicating the color and texture of authentic meat in order to align with consumer preferences and enhance pleasure. The consideration of production costs is a crucial aspect to be taken into account throughout the development of a product such as lab-grown meat, specifically in the context of HCM manufacturing. The development of non-animal-based colorants, additives, and colloids that are more efficient and cost-effective, along with the implementation of sustainable scaffolding techniques for constructing 3D scaffolds and ingestible scaffolding material, holds the potential to revolutionize the meat industry. This vision is shared by researchers and industrialists who aspire to establish a sustainable future for the industry. The application of the electrospinning technology has the potential to be utilized in the development of cost-effective 3D scaffolds, hence potentially leading to a reduction in the overall production cost of CM. Furthermore, there exist potential opportunities for enhanced alignment of muscle fibers in a three-dimensional scaffold, thereby replicating the authentic structure of meat.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Acknowledgements

This research was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2020R1I1A206937911), and the Korean Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries (IPET) through the Agri-Bioindustry Technology Development Program, funded by the Ministry of Agriculture, Food, and Rural Affairs (MAFRA) (Project No. 321028-5), Korea.

Author Contributions

Conceptualization: Alam AMMN, Joo ST. Writing - original draft: Alam AMMN. Writing - review & editing: Alam AMMN, Kim CJ, Kim SH, Kumari S, Lee SY, Hwang YH, Joo ST.

Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

References

Abu-Ghazaleh N, Chua WJ, Gopalan V. 2021. Intestinal microbiota and its association with colon cancer and red/processed meat consumption. J Gastroenterol Hepatol 36:75-88.

Asgar MA, Fazilah A, Huda N, Bhat R, Karim AA. 2010. Nonmeat protein alternatives as meat extenders and meat analogs. Compr Rev Food Sci Food Saf 9:513-529.

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, Sabikun N, Hwang YH, Joo ST. 2021. 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.

Baune MC, Broucke K, Ebert S, Gibis M, Weiss J, Enneking U, Profeta A, Terjung N, Heinz V. 2023. Meat hybrids: An assessment of sensorial aspects, consumer acceptance, and nutritional properties. Front Nutr 10:1101479.

Bomkamp C, Skaalure SC, Fernando GF, Ben-Arye T, Swartz EW, Specht EA. 2022. Scaffolding biomaterials for 3D cultivated meat: Prospects and challenges. Adv Sci 9:2102908.

Carpentieri S, Larrea-Wachtendorff D, Donsì 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.

Cavallini VH, Hargarten PG, Joehnke J. 2006. Vegetable protein meat analogue. US Patent 7,070,827 B2.

Chiang JH, Tay W, Ong DSM, Liebl D, Ng CP, Henry CJ. 2021. Physicochemical, textural and structural characteristics of wheat gluten-soy protein composited meat analogues prepared with the mechanical elongation method. Food Struct 28:100183.

Datar I, Betti M. 2010. Possibilities for an *in vitro* meat production system. Innov Food Sci Emerg Technol 11:13-22.

de Jong A. 2023. Cultured meat scaffolding: Contemporary synergistic methods. M.S. thesis, University of Groningen, Groningen, Netherlands.

Ettoumi YL, Chibane M, Romero A. 2016. Emulsifying properties of legume proteins at acidic conditions: Effect of protein concentration and ionic strength. LWT-Food Sci Technol 66:260-266.

Food and Agriculture Organization [FAO]. 2014. Agriculture, forestry and other land use emissions by sources and removals by sinks. FAO, Rome, Italy.

Fraeye I, Kratka M, Vandenburgh H, Thorrez L. 2020. Sensorial and nutritional aspects of cultured meat in comparison to traditional meat: Much to be inferred. Front Nutr 7:35.

Gamage SMK, Dissabandara L, Lam AKY, Gopalan V. 2018. The role of heme iron molecules derived from red and processed meat in the pathogenesis of colorectal carcinoma. Crit Rev Oncol Hematol 126:121-128.

Gholobova D, Gerard M, Decroix L, Desender L, Callewaert N, Annaert P, Thorrez L. 2018. Human tissue-engineered skeletal muscle: A novel 3D *in vitro* model for drug disposition and toxicity after intramuscular injection. Sci Rep 8:12206.

Goodwin JN, Shoulders CW. 2013. The future of meat: A qualitative analysis of cultured meat media coverage. Meat Sci 95:445-450.

Ismail I, Hwang YH, Joo ST. 2020. Meat analog as future food: A review. J Anim Sci Technol 62:111-120.

Joo ST, Choi JS, Hur SJ, Kim GD, Kim CJ, Lee EY, Bakhsh A, Hwang YH. 2022. A comparative study on the taste characteristics of satellite cell cultured meat derived from chicken and cattle muscles. Food Sci Anim Resour 42:175-185.

Jurie C, Cassar-Malek I, Bonnet M, Leroux C, Bauchart D, Boulesteix P, Hocquette JF. 2007. Adipocyte fatty acid-binding protein and mitochondrial enzyme activities in muscles as relevant indicators of marbling in cattle. J Anim Sci 85:2660-2669.

Kadim IT, Mahgoub O, Baqir S, Faye B, Purchas R. 2015. Cultured meat from muscle stem cells: A review of challenges and prospects. J Integr Agric 14:222-233.

Kanatous SB, Mammen PPA, Rosenberg PB, Martin CM, White MD, Michael DiMaio J, Huang G, Muallem S, Garry DJ. 2009. Hypoxia reprograms calcium signaling and regulates myoglobin expression. Am J Physiol Cell Physiol 296:C393-C402.

Keet CA, Matsui EC, Dhillon G, Lenehan P, Paterakis M, Wood RA. 2009. The natural history of wheat allergy. Ann Allergy Asthma Immunol 102:410-415.

Kumar P, Sharma N, Sharma S, Mehta N, Verma AK, Chemmalar S, Qurni Sazili A. 2021. *In-vitro* meat: A promising solution for sustainability of meat sector. J Anim Sci Technol 63:693-724.

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 11:957.

Kyriakopoulou K, Dekkers B, van der Goot AJ. 2019. Plant-based meat analogues. In Sustainable meat production and processing. Galanakis CM (ed). Academic Press, Wageningen, Netherlands. pp 103-126.

Lee DY, Lee SY, Jung JW, Kim JH, Oh DH, Kim HW, Kang JH, Choi JS, Kim GD, Joo ST, Hur SJ. 2022. Review of technology and materials for the development of cultured meat. Crit Rev Food Sci Nutr 25:8591-8615.

Lee SY, Lee DY, Jeong JW, Kim JH, Yun SH, Joo ST, Choi I, Choi JS, Kim GD, Hur SJ. 2023. Studies on meat alternatives with a focus on structuring technologies. Food Bioprocess Technol 16:1389-1412.

Levi S, Yen FC, Baruch L, Machluf M. 2022. Scaffolding technologies for the engineering of cultured meat: Towards a safe, sustainable, and scalable production. Trends Food Sci Technol 126:13-25.

Listrat A, Lebret B, Louveau I, Astruc T, Bonnet M, Lefaucheur L, Picard B, Bugeon J. 2016. How muscle structure and composition influence meat and flesh quality. Sci World J 2016:3182746.

Lo Surdo JL, Millis BA, Bauer SR. 2013. Automated microscopy as a quantitative method to measure differences in adipogenic differentiation in preparations of human mesenchymal stromal cells. Cytotherapy 15:1527-1540.

Martínez-Villaluenga C, Gulewicz P, Frias J, Gulewicz K, Vidal-Valverde C. 2008. Assessment of protein fractions of three cultivars of *Pisum sativum* L.: Effect of germination. Eur Food Res Technol 226:1465-1478.

Mattice KD, Marangoni AG. 2020. Evaluating the use of zein in structuring plant-based products. Curr Res Food Sci 3:59-66.

Moore GWK, Howell SEL, Brady M, Xu X, McNeil K. 2021. Anomalous collapses of Nares Strait ice arches leads to enhanced export of Arctic sea ice. Nat Commun 12:1.

Moritz MS, Verbruggen SE, Post MJ. 2015. Alternatives for large-scale production of cultured beef: A review. J Integr Agric 14:208-216.

Ng S, Kurisawa M. 2021. Integrating biomaterials and food biopolymers for cultured meat production. Acta Biomater 124:108-129.

Nienow AW, Rafiq QA, Coopman K, Hewitt CJ. 2014. A potentially scalable method for the harvesting of hMSCs from microcarriers. Biochem Eng J 85:79-88.

Ong S, Loo L, Pang M, Tan R, Teng Y, Lou X, Chin SK, Naik MY, Yu H. 2021. Decompartmentalisation as a simple color manipulation of plant-based marbling meat alternatives. Biomaterials 277:121107.

Organisation for Economic Co-operation and Development [OECD], Food and Agriculture Organization [FAO]. 2021. OECD-FAO agricultural outlook 2021-2030. OECD, Paris, France.

Ostrovidov S, Hosseini V, Ahadian S, Fujie T, Parthiban SP, Ramalingam M, Bae H, Kaji H, Khademhosseini A. 2014. Skeletal muscle tissue engineering: Methods to form skeletal myotubes and their applications. Tissue Eng Part B Rev 20:403-436.

Polášek Z, Salek RN, Vašina M, Lyčková A, Gál R, Pachlová V, Buňka F. 2021. The effect of furcellaran or *κ*-carrageenan addition on the textural, rheological and mechanical vibration damping properties of restructured chicken breast ham. LWT-Food Sci Technol 138:110623.

Post MJ. 2014. Cultured beef: Medical technology to produce food. J Sci Food Agric 94:1039-1041.

Post MJ, Hocquette JF. 2017. New sources of animal proteins: Cultured meat. In New aspects of meat quality: From genes to ethics. Purslow PP (ed). Woodhead, Buenos Aires, Argentina. pp 425-441.

Post MJ, Levenberg S, Kaplan DL, Genovese N, Fu J, Bryant CJ, Negowetti N, Verzijden K, Moutsatsou P. 2020. Scientific, sustainability and regulatory challenges of cultured meat. Nat Food 1:403-415.

Rubio NR, Fish KD, Trimmer BA, Kaplan DL. 2019. *In vitro* insect muscle for tissue engineering applications. ACS Biomater Sci Eng 5:1071-1082.

Sanchez-Sabate R, Sabaté J. 2019. Consumer attitudes towards environmental concerns of meat consumption: A systematic review. Int J Environ Res Public Health 16:1220.

Sarlio S. 2018. Towards healthy and sustainable diets: Perspectives and policy to promote the health of people and the planet. Springer, Cham, Switzerland.

Schlater AE, De Miranda MA Jr, Frye MA, Trumble SJ, Kanatous SB. 2014. Changing the paradigm for myoglobin: A novel link between lipids and myoglobin. J Appl Physiol 117:307-315.

Schneider K. 2013. Concentrating on healthy feeding operations: The national school lunch program, cultured meat, and the path to a sustainable food future. J Land Use Environ Law 29:145.

Schreuders FKG, Dekkers BL, Bodnár I, Erni P, Boom RM, van der Goot AJ. 2019. Comparing structuring potential of pea and soy protein with gluten for meat analogue preparation. J Food Eng 261:32-39.

Seah JSH, Singh S, Tan LP, Choudhury D. 2022. Scaffolds for the manufacture of cultured meat. Crit Rev Biotechnol 42:311-323.

Simsa R, Yuen J, Stout A, Rubio N, Fogelstrand P, Kaplan DL. 2019. Extracellular heme proteins influence bovine myosatellite cell proliferation and the color of cell-based meat. Foods 8:521.

Singh A, Kumar V, Singh SK, Gupta J, Kumar M, Sarma DK, Verma V. 2023. Recent advances in bioengineered scaffold for *in vitro* meat production. Cell Tissue Res 391:235-247.

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C. 2006. Livestock's long shadow: Environmental issues and options. Food and Agriculture Organization, Rome, Italy.

Stephens N, King E, Lyall C. 2018. Blood, meat, and upscaling tissue engineering: Promises, anticipated markets, and performativity in the biomedical and agri-food sectors. Biosocieties 13:368-388.

Sun C, Ge J, He J, Gan R, Fang Y. 2021. Processing, quality, safety, and acceptance of meat analogue products. Engineering 7:674-678.

Taghian Dinani S, Zhang Y, Vardhanabhuti B, van der Goot AJ. 2023. Enhancing textural properties in plant-based meat alternatives: The impact of hydrocolloids and salts on soy protein-based products. Curr Res Food Sci 7:100571.

The Good Food Institute [GFI]. 2020. The good food institute. Available from: https://gfi.org/cultivated/#cultivated-meat-101. Accessed at Sep 28, 2023.

The Good Food Institute [GFI]. 2023. The good food institute. Available from: https://gfi.org/cultivated/#industry. Accessed at Sep 28, 2023.

Theethira TG, Dennis M. 2015. Celiac disease and the gluten-free diet: Consequences and recommendations for improvement. Dig Dis 33:175-182.

Thorrez L, Vandenburgh H, Callewaert N, Mertens N, Shansky J, Wang L, Arnout J, Collen D, Chuah M, VandenDriessche T. 2006. Angiogenesis enhances factor IX delivery and persistence from retrievable human bioengineered muscle implants. Mol Ther 14:442-451.

Verbeke W, Marcu A, Rutsaert P, Gaspar R, Seibt B, Fletcher D, Barnett J. 2015. Would you eat cultured meat?: Consumers' reactions and attitude formation in Belgium, Portugal and the United Kingdom. Meat Sci 102:49-58.

Watson E. 2019. FDA approves color additive petition for Impossible Foods' soy leghemoglobin as it gears up for Sept retail launch. FOOD Navigator, Crawley, WV, USA.

Weinrich R. 2019. Opportunities for the adoption of health-based sustainable dietary patterns: A review on consumer research of meat substitutes. Sustainability 11:4028.

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, Vries WD, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S, Murray CJL. 2019. Food in the Anthropocene: The EAT–Lancet commission on healthy diets from sustainable food systems. Lancet 393:447-492.

Zagury Y, Ianovici I, Landau S, Lavon N, Levenberg S. 2022. Engineered marble-like bovine fat tissue for cultured meat. Commun Biol 5:927.

Zernov A, Baruch L, Machluf M. 2022. Chitosan-collagen hydrogel microparticles as edible cell microcarriers for cultured meat. Food Hydroll 129:107632.

Zhang C, Guan X, Yu S, Zhou J, Chen J. 2022. Production of meat alternatives using live cells, cultures and plant proteins. Curr Opin Food Sci 43:43-52.