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Review Article

An Inclusive Review on the Scaling up of Lab-Grown Meat Production Reflecting on its Nutritional Profiling, Challenges and Ethical Implications

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ABSTRACT

The production of cultured meat through Food Biotechnology and Genetic Engineering has revolutionized global sustainability trends as an alternative to conventional meat. This emerging technology aims to enhance production yield and nutritional value by acquiring cell lines, followed by the engineering and expansion of these tissues in a specific medium. However, this development is still in its early stages and faces hindrances such as a lack of high-throughput technology at a wide scale, ethical implications, and consumer acceptance. The constant pressure of finding alternative food sources due to the continuous increase in global food demand has made genetically engineered crops and novel food an area of growing interest, where microbes, algae, and insects are gaining attention for their potential as alternative protein sources. Furthermore, the risk of disease outbreaks is diminished with cell-based meat production, as it does not entail rearing animals in confined environments. Consequently, the need for costly immunization measures against potentially hazardous diseases is obviated. Despite showing great potential due to the increasing demand for meat analogs, this field of research still must overcome significant hurdles to be widely adopted in the mainstream market.

KEYWORDS: Lab-Grown Meat, Sustainable food production, food safety and regulation, future food tech, Food Microbiology.

INTRODUCTION

Meat, a vital source of protein and iron, is the chief dietary source consumed by most people. In response to the escalating global demand for meat, about 70 billion animals are being slaughtered yearly [1]. The conventional meat production paradigm relies on an intricate animal agriculture system which is no longer deemed sustainable due to the outbreaks of zoonotic illnesses like avian flu, African swine fever, and other animal maladies. [2-4]. The field of food biotechnology deals with the use of living entities or their components to develop or alter food products. Conversely, genetic engineering involves altering an organism's genetic makeup using biotechnological techniques like recombinant DNA technology to enhance desired traits. By merging these two domains, lab-developed meat has emerged as a revolutionary product. This innovation includes animal muscle cells that are cultivated in vitro to produce consumable tissue [5-6].

Cultured meat, also known as clean meat or cellular agriculture, offers a more sustainable alternative to conventional animal production and for this purpose, it has gained a lot of attention. The main objectives of this developing technology include lowering the environmental effects of meat production, enhancing animal welfare, solving issues with food security, and encouraging healthy eating habits [6]. Lab-grown meat alternately referred to as, in-vitro meat, synthetic mat, and cell-based meat constitute consumable muscle tissue generated through the controlled cultivation of stem cells within a laboratory setting and protocol by employing tissue engineering techniques and computational simulations to recreate relevant conditions [7]. In essence, cell-based meat is produced by cultivating stem cells originating from an animal for eventual human consumption. Typically, self-renewing and differentiating stem cells are derived from an animal biopsy and placed within a suitable culture medium enriched with essential nutrients, energy sources, growth-promoting hormones, and other requisite variables to facilitate the development and differentiation of these stem cells into mature muscle cells within a bioreactor for large scale production. This results in the formation of muscle fibers, adipose tissue, and other cellular components for shaping muscle tissue. Through the technique of cell (or tissue) culturing, it becomes possible to produce edible animal muscle tissue, commonly recognized as lab-grown meat, by abundantly expanding a limited number of muscle cells into a substantial quantity of tissue. Following food processing steps such as shaping, coloring, and seasoning, these cells are harvested to yield consumable meat end-products [6,8,9]. Cell-based meat has been recognized as one of the "Top 10 Emerging Technologies of 2018" by the World Economic Forum. The forum acknowledged the potential of in-vitro meat production as a reliable strategy for addressing the wide-ranging challenges and moral implications associated with traditional animal-based food production [10-11]

Mark Post's pioneer achievement involved the cultivation of primary skeletal muscle cells. After that, numerous academic institutions and enterprises have pursued this research domain, as documented by [12]. Notably, a U.S.-based startup, Memphis Meats, advanced the field by creating a variety of cultured meat products, including meatballs, beef fajita, chicken, and duck, as reported in the same study. In furtherance to this point, Modern Meadow, a startup enterprise, innovatively created a steak chip composed of cultured meat intermixed with a hydrogel, as supported by [12]. Since the introduction of the introductory cultured meat patty in 2013, a force of private companies has emerged, dedicated to the advancement of cultured meat production [13].

Advancements in food biotechnology and genetic engineering aren't limited to lab-grown meat alone. The food industry in the 21st century has seen a significant rise in unique food products, such as genetically modified (GM) crops [14]. Some prominent instances of GM crops encompass soybeans with herbicide tolerance, corn that resists insects, and rice that has been enriched with vitamins. (GM Science Review Panel, 2003) These cutting-edge food innovations have promoted increased crop production, improved the nutritional value of crops, and contributed to the emergence of functional foods [15].

Purpose of the Study

This detailed examination delves into the world of lab-cultivated meat and cutting-edge food products, touching on the fundamental principles, manufacturing techniques, regulatory aspects, and societal implications tied to these groundbreaking innovations. Furthermore, this investigation delves into the advantages, challenges, and potential effects on society brought about by incorporating food biotechnology and gene manipulation on a worldwide scale. By weaving together insights from scholarly literature, governing documents, and industry reports, this thorough assessment becomes an indispensable resource for decision-makers, regulators, and consumers immersed in the rapidly progressing domain of food biotechnology and genetic alteration.

Food Biotechnology and Genetic Engineering

Food biotechnology, commonly known as food biotech, involves the application of biotechnological methods to enhance and modify our food products, and production processes, and secure the food supply chain. By utilizing living organisms like bacteria or enzymes, as well as genetic engineering principles, it aims to improve various aspects of food such as taste, nutritional content, shelf-life, and pest resistance.

Genetic engineering is an aspect of food biotechnology that includes the hands-on alteration of an organism's genetic makeup using advanced biotechnological tools like recombinant DNA methods, gene editing, and gene silencing. Through this approach, we can add, remove, or alter genetic materials in a living organism to achieve specific desired characteristics.

History and Evolution

The journey of food biotechnology can be traced back to the ancient practice of fermentation, which dates back thousands of years and is responsible for producing goods like beer, wine, cheese, and yogurt [16]. However, the most notable achievements in this field took shape during the 20th century with groundbreaking discoveries in genetics and DNA. During the 1970s, the advent of recombinant DNA technology paved the way for transferring specific genes between species, ultimately leading to the birth of genetically modified organisms (GMOs) [17]. Scientists were then able to create the first GMO in 1973, marking the beginning of an era where they could genetically alter a wide range of crops and livestock to enhance their desirable traits [18]. In 1994, the Flavr Savr tomato, the inaugural genetically modified (GM) food product, was given the green light for commercialization, signifying the dawn of the contemporary era of genetic engineering in food. After that event, various GM crops have been created and extensively embraced in worldwide agriculture, including Bt cotton, Roundup Ready soybean, and Bt corn [19].

Current State and Application

Food biotechnology and genetic engineering have advanced rapidly in contemporary times, and they now impact various aspects of food production:

1. Enhancing production: Thanks to genetic engineering, agriculture has benefited from substantial improvements in productivity and quality. GMO crops have become more resistant to pests, diseases, and environmental stress, leading to greater yields [20]. Example: Bt cotton is a prominent example of GMO crops that have revolutionized agriculture. By incorporating a gene from the bacterium *Bacillus thuringiensis* into the cotton plant, this crop variety is resistant to pests like the cotton bollworm, ultimately improving yield and reducing pesticide dependence (ISAAA).

2. Nutritional upgrades: Scientists have developed genetically engineered crops with boosted nutrient content, such as Golden Rice, which offers higher levels of vitamin A. This helps to address malnutrition and micronutrient deficiencies [21]. Example: Biofortified sorghum is another genetically modified crop designed to address malnutrition. This enhanced

grain contains elevated levels of essential micronutrients, such as iron and zinc, as well as increased digestibility, offering a promising solution to undernourishment, particularly in developing countries where sorghum is a dietary staple [22].

3. Food quality and safety: The advancements in genetic engineering have played a substantial role in enhancing the quality of food products. These technologies not only assist in improving the taste, smell, and texture of food items, but they also extend their shelf life. Moreover, the use of genetically modified organisms (GMOs) in crops can potentially lower the risk of food allergies, decrease toxic and anti-nutritional substances, and promote overall food safety [23].

For instance, the production of Golden Rice, a genetically modified crop, minimizes food allergens while also improving its nutritional value [24].

4. Lab-grown meat and Novel food products:

In the realm of sustainable food options, lab-grown meat - also known as cultured, in-vitro, or cell-based meat - presents an innovative alternative to conventional animal-derived meat production [25]. This groundbreaking achievement, which has blossomed with the aid of tissue engineering and cellular agriculture, offers considerable benefits in terms of mitigating environmental damage, conserving resources, and preventing cruel treatment of animals [26]. For example, California-based food start-up, Memphis Meats, has developed lab-grown meat products that are indistinguishable in taste from conventional meat products.

As advancements in food biotechnology and genetic engineering continue to make strides, we will witness the creation of innovative food products and applications. These developments will aim to confront worldwide food security concerns, tackle nutritional hurdles, and contribute to the quest for sustainable solutions.

Lab Grown Meat:

Cultivated meat, commonly known as lab-grown, cell-based, clean, or slaughter-free meat, is essentially meat produced by growing animal cells in a regulated setting [27]. To achieve this, a small tissue sample is usually taken from an animal via a biopsy. Next, the appropriate cells are extracted, multiplied, and developed into muscle fibers. Finally, these fibers are collected and transformed into a variety of meat products [28].

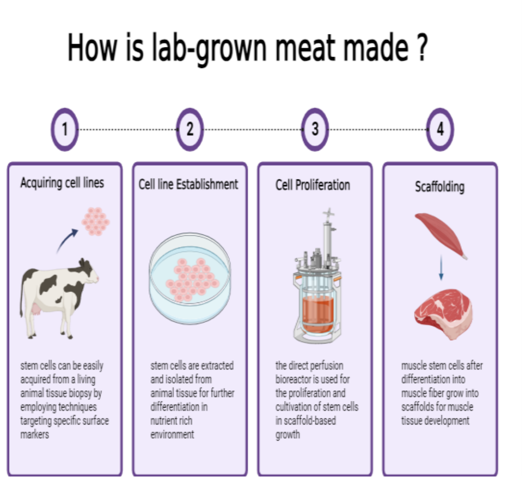

Fig 1: Process involved in the formation of in-vitro meat production. Image is created using biorender.

Technologies Used:

Lab-grown meat production mainly consists of three fundamental steps: (1) acquiring cell lines, (2) cultivating and expanding cells, and (3) engineering tissues [29]. Several essential technologies are employed in this process, such as:

Acquiring Cell Lines: Stem cells represent a class of progenitor cells competent in both extensive proliferation and differentiation into various distinct cell types, each fortified with specialized functions [30].

These cells can be readily acquired from a living animal tissue biopsy through enzymatic digestion, mechanical disruption, and purification, employing techniques targeting specific surface markers [31]. Embryonic stem (ES) cell lines offer limitless regenerative potential, yet the risk of accumulating mutations across successive generations and the need for specific stimulation for muscle cell development are inherent challenges. On the contrary, myosatellite cells possess limited regenerative capacity but exhibit a closer resemblance to the natural process of myogenesis. These satellite cells undergo rapid maturation into myotubes and mature myofibrils, executing the preferred cellular source for the formation of skeletal muscle tissue [32]. While various cell sources are suitable to produce in-vitro meat, distinct ex vivo expansion and differentiation protocols must be employed for each cell type, due to their unique growth and developmental characteristics [28, 33-34]. To ensure a reliable and consistent source of cells for production, continuous or immortalized cell lines can be generated through genetic modification techniques. These cell lines can then be cultivated indefinitely.

The proliferation of cell and cell media:

Following the isolation of stem cells, expansion is vital to achieve the required cell quantities. Conventional laboratory-scale vessels, such as flasks or dishes, prove insufficient to meet the demands of the market, obligating the development of a large-scale bioreactor system [35]. The design of the bioreactor plays a pivotal role in promoting tissue development, and its effectiveness in scaled-up cell-based meat production, ensuring adequate oxygen perfusion during cell seeding and scaffold-based development. Bioreactors offer a higher means of mass transfer between the culture media and the cells, thereby optimizing oxygen perfusion. A remarkable bioreactor design, the rotating wall vessel, operates at a speed that thoroughly balances centrifugal, drag, and gravitational forces. The bioreactor design should enable three-dimensional culture immersion in the medium, facilitating the creation of tissue with a structure closely resembling that found in vivo, all while minimizing shear stress.

Another bioreactor variant, the direct perfusion bioreactor, proves better suited for scaffold-based growth. Here, a porous scaffold facilitates medium circulation, with gas exchange occurring in an external fluid loop. This configuration boasts a high mass transfer rate but implies considerable shear stress [36]. In the context of stem cell development and their differentiation into muscle cells, a specialized cell culture medium is crucial. Danoviz and Yablonka-Reuveni successfully employed Dulbecco's Modified Eagle Medium (DMEM), supplemented with Fetal Bovine Serum (20%) and Horse Serum (10%) to advance the proliferation and differentiation of myosatellite cells. DMEM represents a four-fold concentrated formulation of vitamins and amino acids derived from Basal Medium Eagle (BME). It includes constituents such as 4.5 g/L glucose, 0.11 g/L sodium pyruvate, 100 U/mL penicillin, 0.0000001 g/L streptomycins, and 0.004 M l-glutamine.

Fetal bovine serum (20%) is enriched with fibroblast and insulin-like growth factors, is heat-inactivated, and serves as a catalyst for myoblast differentiation and proliferation. The inclusion of horse serum (10%) is associated with its remarkable capacity to enhance myoblast differentiation and proliferation. After two weeks in culture, the results were promising, with 81% of the cultures demonstrating tissue adherence to the culture vessel, 63% exhibiting self-healing capabilities, and 74% displaying cell proliferation through a self-organized approach. Notably, tissue expansion exceeded 14% when fetal bovine serum was employed as the nutritional medium and over 13% with the use of mushroom extract. A groundbreaking discovery was made in the growth of goldfish explant tissue within a serum-free medium. Overcoming the most formidable obstacle in cell-based meat production involves substituting natural extracts for serum-free media—a challenge that scientists and companies are ardently addressing [37]. Growth factors play a pivotal dual role in facilitating cell proliferation and growth. The approach includes the possibility of incorporating purified growth factors or hormones, sourced from plants, animals, or transgenic bacterial species, into the culture medium to produce recombinant proteins [38].

Furthermore, the methodology highlights the importance of employing a cost-effective serum-free medium and implementing real-time monitoring of various parameters including pH, dissolved oxygen, carbon dioxide levels, essential nutrient concentrations, and metabolic waste. Simultaneously, medium recycling, automated removal of hazardous wastes, and nutrient replenishment guided by monitoring feedback are pivotal strategies to optimize resource utilization and minimize production costs [39-40].

Cellular scaffolds are structures that are compatible with living organisms and can be either natural or synthetic in origin. These scaffolds assist in organizing cells into three-dimensional tissue structures, facilitating cell differentiation and functional development [41]. This process yields meat that is tender and devoid of bones, suitable for applications like hamburger and sausage production. However, a notable limitation of this method is its inability to generate highly structured or three-dimensional meat, such as steak cuts. A potential strategy for advancing in vitro meat production involves the co-cultivation of myoblasts and fibroblasts. Upon achieving the requisite cell quantities, these cells undergo stimulation to differentiate into myotubes, adipocytes, or other mature cell types within muscle tissue. Given that the degree of cell maturity significantly influences characteristics, structure, and nutrient composition, encompassing proteins, fatty acids, and vitamins, the maturity level of the final cells assumes primary importance at this stage [42].

Although muscle stem cells are presumed to possess a substantial potential for myogenic differentiation, it's crucial to acknowledge that the diameter, length, and protein content of myofibers produced ex vivo can vary considerably based on the specific culture conditions. These variations may result in values significantly lower than those observed in genuine muscle fibers. Consequently, optimizing the differentiation state and enhancing the maturity of the differentiated cells represent critical objectives, mirroring the natural progression of in vivo muscle tissue development [43-45].

Due to these technologies, a vast array of potential animal-free meat products has emerged, including beef, chicken, seafood, and more complex, structured meat alternatives.

Market Overview

The burgeoning lab-grown meat industry is just starting to take root, with a majority of its offerings poised to enter the market soon. This sector has seen considerable investment and growth due to an increasing appetite for environmentally friendly and humane food production, concerns over food security, and advancements in technology. Several prominent companies in the market, including Memphis Meats, Mosa Meat, Aleph Farms, and SuperMeat, are passionately striving to make lab-grown meat a standard item on grocery store shelves.

Nutritional Perspective of Lab-Grown Meat Vs Animal Meat:

The nutritional content of lab-grown meat has been extensively examined to determine if it can serve as a viable alternative to traditional animal meat. Studies have shown that lab-grown meat closely resembles conventional meat in terms of its macronutrient composition, including protein, fat, and carbohydrates. In a recent investigation conducted, it was found that lab-grown meat boasted a protein content comparable to that of beef while containing lower levels of saturated fat. Additionally, lab-grown meat holds the potential to be tailored to meet specific nutritional needs by adjusting the levels of certain nutrients as required.

1. Fatty Acid Profile: The health implications of lab-grown meat have been explored by examining its composition of fatty acids. In a recent study [46], the researchers analyzed the profile of fatty acids present in lab-grown meat and discovered that it exhibited a generally beneficial ratio of omega-6 to omega-3 fatty acids. This ratio has been linked to a lowered risk of chronic diseases. Nevertheless, additional research is still necessary to optimize the fatty acid composition of lab-grown meat to closely resemble that of traditional meat.

2. Vitamin and Mineral Content: Studies investigating the vitamin and mineral content of lab-grown meat compared to animal meat have yielded varying results. Some research indicates that lab-grown meat may contain lower levels of specific vitamins and minerals, such as vitamin B12 and iron [47]. However, other studies have reported similar levels between lab-grown and traditional meat [46]. It is important to conduct further research to ensure that lab-grown meat can adequately provide essential nutrients as traditional meat does.

3. Bioavailability and Safety: The presence of nutrients and the possible health risks of lab-created meat have attracted significant interest. While research suggests that lab-grown meat retains favorable nutrient bioavailability [48], additional inquiry is necessary to substantiate this assertion. Additionally, comprehensive safety evaluations encompassing microbial contamination and the potential for allergic reactions are imperative to establishing the practicality of lab-grown meat production as a viable substitute for traditional meat [49].

Public Opinion and Perception

1. Consumer Attitudes and Willingness to Consume: The willingness of consumers to embrace lab-grown meats and innovative food products is crucial for the success of food biotechnology and genetic engineering advancements. People's opinions on futuristic food items such as lab-produced meat are often divided, with some individuals displaying curiosity and openness, while others remain doubtful [50]. Key factors driving the acceptance of these products include environmental consciousness, health considerations, and inquisitiveness [49]. Although interest in lab-grown meat is on the rise, concerns regarding its taste, texture, and safety continue to influence consumer attitudes and their willingness to consume these products.

2: Analyzing Ethical Factors: When discussing lab-grown meat and cutting-edge food products, the ethical implications surrounding their development and consumption play a pivotal role in shaping public opinion. Advocates of lab-grown meat assert that by significantly minimizing the suffering traditionally associated with meat production, it can alleviate environmental problems related to livestock farming [51]. On the other hand, detractors voice concerns regarding the long-term unknown hazards, the concept of naturalness, and the potential unforeseen consequences of incorporating these novel products into our food systems [52].

3: Case study - Exploring moral implications: To further show the moral sides of lab-grown meat and new food types, let's look at a company called "MeatGen Corp." MeatGen Corp. recently figured out a way to make fake meat using cell farming. They claim this process can greatly cut down the bad effects on the environment and moral issues that often come with normal meat making.

Those who support MeatGen Corp.'s tech say that if used on a large scale, it could lead to a lot fewer animals being raised and killed for people to eat, which would significantly lower animal suffering. Also, they point out that since this meat is made using way fewer resources and causing less pollution, it could help fight climate change, land damage, and water pollution [53].

However, critics question how safe it will be for people to eat lab-grown meat long-term, as the safety and possible side effects are not yet fully known. They also challenge whether these products can satisfy the human want for "natural" foods, as the making process strays from traditional farming practices. Further, they warn that the widespread adoption of lab-grown meat could have unforeseen impacts on both individual and group food choices and global food systems and economies.

This case study shows the complex moral landscape surrounding the development, production, and consumption of lab-grown meat and other pioneering food products. Balancing the potential benefits and risks requires ongoing exploration and discussion among many stakeholders.

4: Factors Influencing Public Opinion: Many elements play a role in shaping public opinion regarding lab-grown meat and innovative food products, including aspects like age, cultural distinctions, level of education, political leanings, and faith in science and technology. Studies indicate that younger people and those with advanced education tend to be more open to embracing new food technologies [54]. Additionally, individuals who are more adventurous when it comes to trying new foods and have a heightened concern for the environment and animal welfare are generally more receptive to the idea of lab-grown meat [55].

5: Implications for Policy and Regulatory Factors: When it comes to influencing government policies and regulations regarding lab-grown meat and groundbreaking food products, the thoughts and feelings of the general public carry significant weight. Governmental bodies need to strike a balance between endorsing state-of-the-art food technologies and addressing the public's safety concerns, ethical questions, and environmental ramifications. In the United States, the FDA (2018) conducted meetings with various parties to talk about the essential regulatory structures for such products and is in the process of establishing suitable guidelines. Openness and active public participation in these procedures are essential components, as they can improve trustworthiness and popular endorsement of these innovative food items.

Challenges and Future Prospects

1: Obstacles and Upcoming Opportunities:

In recent times, the progress and commercialization of lab-produced meat and innovative food items have shown great potential. Nonetheless, various hurdles must be overcome to guarantee their widespread adoption in the mainstream market. This section provides a critical examination of the challenges posed by biotechnological and genetic engineering approaches in food production and outlines potential paths for future development.

2: Technical barriers and scalability: Creating large quantities of lab-grown meat and innovative food items is a crucial step that must be refined [12]. The present methods used to create animal-based proteins encounter several hurdles, such as expanding cell cultures, developing appropriate biomaterials, and incorporating advanced bioprocesses. To overcome these obstacles, significant investments in research, specialized production infrastructure, and qualified experts are essential.

3: Regulatory approval and labeling: As the market for lab-grown meat and innovative food products continues to grow, regulatory frameworks are still in the process of development. Securing regulatory approval is essential for ensuring the safety and successful commercialization of these products. It is important to establish well-defined guidelines, standards, and labeling practices [46]. This will require collaborative efforts from various stakeholders such as government agencies, research institutions, and the industry itself.

4. Consumer acceptance and adoption: Public opinion and perceptions of lab-grown meat and other innovative food products will play a significant role in determining their success. What influences consumers' ability to accept these products primarily comes down to their taste, cost, quality, and safety, as well as both the environmental and ethical impressions they hold [55]. To establish trust and promote a more comprehensive adoption of these new food items, it is crucial to address these influencing factors.

5. Future research and development directions: Future research ought to concentrate on finding innovative solutions to surpass technical obstacles, cut down the expenses of production, and boost the eco-friendliness of lab-grown meat and unique food items. This encompasses enhancing cell culturing methods, inventing alternative biodegradable frameworks, and investigating plant-derived proteins (Specht et al., 2018). By bringing together diverse stakeholders, we can expedite the R&D process and address issues related to ethics, public opinion, and product safety [56].

Key areas that require further policy analysis include:

- Evaluating current regulatory frameworks and identifying gaps or inadequacies: At present, it is unclear how products like lab-grown meat will be regulated, with jurisdictions deliberating over food vs drug classifications [57]. Analyses are needed to determine appropriate regulatory bodies and standards.
- Risk assessment and safety testing: Robust risk assessment frameworks and safety testing protocols need to be developed to evaluate potential human health and environmental impacts of novel foods [58]. Policy analyses should inform scientific testing requirements.

- Labelling standards: There is considerable debate around effective labeling for new food technologies to provide consumers clarity without being overly burdensome for producers [59]. Policy options must balance transparency, consumer rights, and manufacturing feasibility.

- Intellectual property protections: Policy guidelines are required to stimulate innovation in cellular agriculture and genetically engineered foods through appropriate IP protections and public research funding [60].

- International harmonization of regulations: Varied regulations across countries can hamper uptake and cause trade disruptions. Analyzing mechanisms for regulatory alignment can encourage consistent standards.

Integrating perspectives from a range of stakeholders, including corporations, consumer advocacy groups, moral philosophers, and the scientific community, is essential when conducting policy studies. In addition, policy solutions must evaluate the benefits and drawbacks of regulatory actions to find the right balance between encouraging innovation for the greater good and addressing moral and safety concerns. The responsible management of innovative food technology will need careful policy analysis and open public debate.

CONCLUSION

Cultured meat is a technology with great potential as a sustainable alternative to conventional meat, and this trend has seen a major surge in the current market. The implication of cultured meat can avoid environmental and animal welfare-related issues concerning livestock farming and will provide more efficient ways for meat production to ensure the sustainability of food demand for the growing population. For the production of lab-grown meat, primary cultures are established by taking the muscle cells from an animal and growing them in a suitable medium. Hence, producing a surplus amount of meat from a limited number of primary cell cultures using genetic modification techniques. The lab-grown meat industry has just started to take root, but the process of regulating lab-grown meat has to be accelerated and more research should be done to incorporate advanced bioprocesses and overcome technical obstacles to legally introduce it as a novel food product in the market. On the other hand, novel food products are a highlighted trend as a key answer to meet the criteria for growing food demand. As the market for lab-grown meat and innovative food products continues to grow, regulatory frameworks and surveys are still in the process of development and are mainly focused on finding solutions to some discouraged elements, factors, and potential obstacles. Lastly, further research on lab-grown meat and novel food products is a necessity to examine which aspect of this technology can play a greater role in influencing consumers' acceptance of these innovative items.

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REFERENCES

[1]. Dopelt, K., et al. (2019). “Environmental Effects of the Livestock Industry: The Relationship between Knowledge, Attitudes, and Behavior among Students in Israel”. International journal of environmental research and

public health, 16(8), 1359. DOI: 10.3390/ijerph16081359

[2]. Dixon, L. K., Stahl, K.,et al. (2020). “African Swine Fever Epidemiology and Control”. Annual review of animal biosciences, 8, 221–246. DOI:10.1146/annurev-animal-021419-083741

[3]. Singh, A., Verma, V., et al. (2022). “Stem cells-derived in vitro meat: from petri dish to dinner plate”. Critical reviews in food science and nutrition, 62(10), 2641–2654. DOI: 10.1080/10408398.2020.1856036

[4]. Taylor, R. A., Condoleo, R., Simons, R. R. L., Gale, P., Kelly, L. A., & Snary, E. L. (2020). “The Risk of Infection by African Swine Fever Virus in European Swine Through Boar Movement and Legal Trade of Pigs and Pig Meat”. Frontiers in veterinary science, 6, 486. DOI: 10.3389/fvets.2019.00486

[5]. King, David & Dalton, Howard et al.(2003). GM Science Review: An open review of the science relevant to GM crops and food based on the interests and concerns of the public. GM Science Review Panel. 10.13140/2.1.2195.2800.

[6]. Bhat, Z. F., Kumar, S., & Bhat, H. F. (2015). “In vitro meat production: challenges and benefits over conventional meat production”. Journal of Integrative Agriculture, 14(2), 241-248. DOI:10.1016/S2095-3119(14)60887-X

[7]. Mengistie, D. (2020). “Lab-growing meat production from stem cells”. Journal of Nutrition & Food Sciences, 3(1), 015. https://doi.org/10.1080/23311932.2017.1320814

[8]. Arshad, M. S., Javed, M., Sohaib, M., Saeed, F., Imran, A., & Amjad, Z. (2017). “Tissue engineering approaches to develop cultured meat from cells: A mini review”. Cogent Food & Agriculture, 3(1), 1320814 https://doi.org/10.1080/23311932.2017.1320814

[9]. Kadim, I. T., Mahgoub, O., Baqir, S., Faye, B., & Purchas, R. (2015). “Cultured meat from muscle stem cells: A review of challenges and prospects". Journal of Integrative Agriculture, 14(2), 222-233. https://doi.org/10.1016/S2095-3119(14)60881-9

[10]. Jiang, G., Ameer, K., Kim, H., Lee, E. J., Ramachandraiah, K., & Hong, G. P. (2020). “Strategies for Sustainable Substitution of Livestock Meat”. Foods (Basel, Switzerland), 9(9), 1227. DOI: 10.3390/foods9091227

[11]. Lee, H. J., Yong, H. I., Kim, M., Choi, Y. S., & Jo, C. (2020). “Status of meat alternatives and their potential role in the future meat market - A review”. Asian-Australasian journal of animal sciences, 33(10), 1533–1543. DOI: 10.5713/ajas.20.0419

[12]. Stephens, N., Di Silvio, L., Dunsford, I., Ellis, M., Glencross, A., & Sexton, A. (2018). “Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture”. Trends in food science & technology, 78, 155–166. DOI: 10.1016/j.tifs.2018.04.010

[13]. Choudhury, D., Tseng, T. W., & Swartz, E. (2020). The Business of Cultured Meat. Trends in biotechnology, 38(6), 573–577. DOI: 10.1016/j.tibtech.2020.02.012

[14]. James, C. (2015). “Global Status of Commercialized Biotech/GM Crops”. ISAAA Brief 51-2015 Ithaca, NY, USA. (ISAAA).

[15]. Qaim, M. (2015). Genetically Modified Crops and Agricultural Development. Palgrave Pivot. 978-1-349-95844-3

[16]. Forster, A. C., & Church, G. M. (2006). “Towards synthesis of a minimal cell ”. Molecular Systems Biology, 2, 45. DOI: 10.1038/msb4100090

Post, M. J. (2012). “Cultured meat from stem cells: challenges and prospects”. Meat Science, 92(3), 297-301 DOI: 10.1016/j.meatsci.2012.04.008

[17]. Cohen, S. N., Boyer, H. W., & Helling, R. B. (1973). “Construction of biologically functional bacterial plasmids in vitro”. Proceedings of the National Academy of Sciences, 70(11), 3240-3244. doi: 10.1073/pnas.70.11.3240

[18]. Fraley, R. T., Rogers, S. G., & Horsch, R. B. (1985). “Genetic transformation in higher plants”. Critical Reviews in Plant Sciences, 3(1), 1-46. https://doi.org/10.1080/07352688609382217

[19]. James, C. (2016). “Global Status of Commercialized Biotech/GM Crops”. ISAAA Brief, 52, 12.

[20]. Qaim, M. (2009). “The economics of genetically modified crops”. Annual Review of Resource Economics, 1, 665-694.

[21]. Paine, J.A., Sipton, C.A.,et al. (2005). “Improving the nutritional value of Golden Rice through increased pro-vitamin A content”. Nature biotechnology, 23 (4), 482–487. DOI: 10.1038/nbt1082

[22]. Drakakaki, G., Marcel, S.,et al. (2005). “Endosperm-specific co-expression of recombinant soybean ferritin and Aspergillus phytase in maize results in significant increases in the levels of bioavailable iron”. Plant Molecular Biology, 59(6), 869-880. DOI: 10.1007/s11103-005-1537-3

[23]. Herman, E. M. (2003). “Genetically modified soybeans and food allergies”. Journal of Experimental Botany, 54(386), 1317-1319. DOI: 10.1093/jxb/erg164

[24]. Potrykus, I. (2010). “Golden rice and beyond”. Plant Physiology, 154(2), 471-474. DOI: 10.1104/pp.125.3.1157

[25]. Post, M. J. (2012). “Cultured meat from stem cells: challenges and prospects”. Meat Science, 92(3), 297-301 DOI: 10.1016/j.meatsci.2012.04.008

[26]. Genovese, N. J., Domeier, T. L., et al. (2017). “Enhanced development of skeletal myotubes from porcine induced pluripotent stem cells”. Scientific Reports, 7, 41833. doi: 10.1038/srep41833

[27]. Post, M. J. (2014). “Cultured meat from stem cells: challenges and prospects”. Meat Science, 92(3), 297-301. DOI: 10.1016/j.meatsci.2012.04.008

[28]. Stephens, N., Di Silvio, L., et al. (2018). “Bringing cultured meat to market: technical, socio-political, and regulatory challenges in cellular agriculture”. Trends in Food Science & Technology, 78, 155-166. DOI: 10.1016/j.tifs.2018.04.010

[29]. Bhat, Z.F., Morton, J.D., et al.(2019). “Technological, regulatory, and ethical aspects of in vitro meat: a future slaughter-free harvest”. Frontiers in Nutrition, 6, 52. DOI: 10.1111/1541-4337.12473

[30]. Dodson, M. V., Allen, R. E., Du, M., Bergen, W. G., Velleman, S. G., Poulos, S. P., Fernyhough-Culver, M., Wheeler, M. B., Duckett, S. K., Young, M. R., Voy, B. H., Jiang, Z., & Hausman, G. J. (2015). “INVITED REVIEW: Evolution of meat animal growth research during the past 50 years: Adipose and muscle stem cells”. Journal of animal science, 93(2), 457–481. DOI: 10.2527/jas.2014-8221

[31]. Ding, S., Wang, F., Liu, Y., Li, S., Zhou, G., & Hu, P. (2017). “Characterization and isolation of highly

purified porcine satellite cells". Cell death discovery, 3, 17003.DOI: 10.1038/cddiscovery.2017.3

[32]. Bach, A. D., Stem-Straeter, J., Beier, J. P., Bannasch, H., & Stark, G. B. (2003). "Engineering of muscle tissue". Clinics in plastic surgery, 30(4), 589–599.

DOI: 10.1016/s0094-1298(03)00077-4

[33]. Fish, K. D., Rubio, N. R., Stout, A. J., Yuen, J. S. K., & Kaplan, D. L. (2020). "Prospects and challenges for cell-cultured fat as a novel food ingredient". Trends in food science & technology, 98, 53–67. DOI: 10.1016/j.tifs.2020.02.005

[34]. Zhang, G., Zhao, X., Li, X., Du, G., Zhou, J., & Chen, J. (2020). "Challenges and possibilities for bio-manufacturing cultured meat". Trends in Food Science & Technology, 97, 443-450. https://doi.org/10.1016/j.tifs.2020.01.026

[35]. Post, M. J., Levenberg, S., Kaplan, D. L., Genovese, N., Fu, J., Bryant, C. J., ... & Moutsatsou, P. (2020). "Scientific, sustainability and regulatory challenges of cultured meat". Nature Food, 1(7), 403-415. https://doi.org/10.1038/s43016-020-0112-z

[36]. Kurt, E., Klont, E., Ergün, Ö., & Klont, R. (2021). "White paper cell cultured meat".

[37]. Benjaminson, M. A., Gilchriest, J. A., & Lorenz, M. (2002). "In vitro edible muscle protein production system (MPPS): stage 1, fish". Acta astronautica, 51(12), 879–889. DOI: 10.1016/s0094-5765(02)00033-4

[38]. Houdebine L. M. (2009). "Production of pharmaceutical proteins by transgenic animals". Comparative immunology, microbiology and infectious diseases, 32(2), 107–121. DOI: 10.1016/j.cimid.2007.11.005

[39]. Allan, S. J., De Bank, P. A., & Ellis, M. J. (2019). "Bioprocess design considerations for cultured meat production with a focus on the expansion bioreactor". Frontiers in Sustainable Food Systems. 3, 44.

[40]. Guan, X., Lei, Q., Yan, Q., Li, X., Zhou, J., Du, G., & Chen, J. (2021). "Trends and ideas in technology, regulation and public acceptance of cultured meat". Future Foods, 3, 100032. https://doi.org/10.1016/j.fufo.2021.100032

[41]. Datar, I., & Betti, M. (2010). "Possibilities for an in vitro meat production system". Innovative Food Science & Emerging Technologies, 11(1), 13-22. http://dx.doi.org/10.1016/j.ifset.2009.10.007

[42]. Wuyi, L. A. (2019). "Review on the Genetic regulation of myogenesis and muscle development". American Journal of Biochemistry and Biotechnology, 15(1). https://doi.org/10.3844/ajbbsp.2019.1.12

[43]. Braga, M., Simmons, Z., Norris, K. C., Ferrini, M. G., & Artaza, J. N. (2017). "Vitamin D induces myogenic differentiation in skeletal muscle derived stem cells". Endocrine connections, 6(3), 139–150. DOI: 10.1530/EC-17-0008

[44]. Lamarche, É., AlSudais, H., Rajgara, R., Fu, D., Omaiche, S., & Wiper-Bergeron, N. (2021). "SMAD2 promotes myogenin expression and terminal myogenic differentiation". Development (Cambridge, England), 148(3).

[45]. Park, S. Y., Yun, Y., Lim, J. S., Kim, M. J., Kim, S. Y., Kim, J. E., & Kim, I. S. (2016). "Stabilin-2 modulates the efficiency of myoblast fusion during myogenic differentiation and muscle regeneration". Nature communications, 7, 10871.

[46]. Chriki, S., & Hocquette, J. (2020b). “The Myth of Cultured Meat: A review”. Frontiers in Nutrition, 7,7. DOI: 10.3389/fnut.2020.00007

[47]. Kumar, P., Sharma, N., etal. (2021). “In-vitro meat: a promising solution for sustainability of the meat sector”. Journal of Animal Science and Technology, 63(4), 693–724. DOI: 10.5187/jast.2021.e85

[48]. Fraeye, I., Kratka, M., Vandenburgh, H. H., & Thorrez, L. (2020). “Sensorial and nutritional aspects of cultured meat in comparison to traditional meat: much to be inferred”. Frontiers in Nutrition, 7, 35. DOI: 10.3389/fnut.2020.00035

[49]. Bryant, C., & Barnett, J. (2018). “Consumer acceptance of cultured meat: A systematic review”. Meat Science, 143, 8–17.

[50]. Verbeke, W., Marcu, A., et al. (2015). "Would you eat cultured meat?": Consumers' reactions and attitude formation in Belgium, Portugal, and the United Kingdom”. Meat Science, 102, 49-58. DOI: 10.1016/j.meatsci.2014.11.013

[51]. Tuomisto, H. L., et al. (2014). “Environmental impacts of cultured meat production”. Environmental Science & Technology, 45(14), 6117-6123.

[52]. Siegrist, et al. (2018). “Perceived naturalness and evoked disgust influence acceptance of cultured meat”. Meat Science, 139, 213-219.

[53]. Martinez, et al. (2020). “Life cycle analysis of cultured meat production: A systematic review”. Journal of Cleaner Production, 277, 123462.

[54]. Hartmann, C., & Siegrist, M. (2017). “Consumer perception and behaviour regarding sustainable protein consumption: a systematic review”. Trends in Food Science & Technology, 61, 11-25. DOI:10.1016/j.tifs.2016.12.006

[55]. Bryant, C., & Dillard, C. (2019). “The impact of framing on acceptance of cultured meat”. Frontiers in Nutrition, 6, 103.

[56]. Lynch, J., & Pierrehumbert, R. (2019). “Climate change impacts cultured meat and beef cattle”. Frontiers in Sustainable Food Systems, 3, 7.

[57]. Penn, J. (2018). "Cultured Meat: Lab-Grown Beef and Regulating the Future Meat Market”. UCLA Journal of Environmental law and Policy, 36, 104.

[58]. Pusztai, A. (2002). “Can science give us the tools for recognizing possible health risks of GM food?” Nutr Health, 16(2), 73-84. DOI: 10.1177/026010600201600202

[59]. Uddin, A., & Gallardo, R. K. (2021). “Consumers’ willingness to pay for organic, clean labels, and processed with a new food technology: an application to ready meals”. The International Food and Agribusiness Management Review, 24(3), 563-579. DOI:10.22434/IFAMR2020.0127

[60]. Shelton, A. C., & Tracy, W. F. (2017). “Cultivar Development in the U.S. Public Sector”. Crop Science, 57, 1823-1835. DOI:10.2135/cropsci2016.11.0961