Economic Viability of Cultured Meat

A Thesis Presented as part fulfilment for the Award of Master of Science in Food Business Management and Technology by

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Declaration

I hereby certify that the material, which I now submit for assessment on the programme of study leading to the award of M.Sc in Food Business Management and Technology, is entirely my own work and has not been taken from the work of others save to the extent that such work has been cited and acknowledged within the text of my own work. No portion of work contained in this thesis has been submitted in support of an application for another degree or qualification to this or any other institution.

Signed:____________________ Date:__________

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I hereby certify that the unreferenced work described in this thesis and being submitted for the award of M.Sc in Food Business Management and Technology is entirely the work of Lauren Mc Conville. No portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification to this or any other institution.

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Abstract

Cultured meat is a promising prospect in the food industry. An increasing population, combined with a correlating increase in meat consumption, further facilitated by sustainability and food safety concerns in the meat industry have been the key drivers for development of cultured meat. Cultured meat is still in its early stages of development and requires much work in its scalability to bring it to the marketplace and to make it an economically viable food product for human consumption. While much theoretical and scientific background work has been completed in this field, huge challenges remain in reducing production costs. This research outlines the current state of the industry and presents the key cost contributors to cultured meat production. Such costs include medium components, bioreactors, building and equipment and labour, among many others. Other technical aspects of the production process have been explored, such as cell source and cell doubling time as they will ultimately contribute to overall efficiency and production costs. Currently, cultured meat is not being produced at a scale or cost that is affordable to the consumer and so, key areas for cost reduction have been explored and presented as a means of making cultured meat a more economically viable alternative to conventional meat.

List of Abbreviations

3D	Three-dimensional
ADHB	Agriculture and Horticulture Development Board
BSE	Bovine Spongiform Encephalopathy
EEA	Essential Amino Acids
EFSA	European Food Safety Authority
EU	European Union
FAO	Food and Agriculture Organisation
FBS	Fetal Bovine Serum
FDA	Food and Drug Administration
FGF	Fibroblast Growth Factor
GHG	Greenhouse gas
GFI	Good Food Institute
IPCC	Intergovernmental Panel on Climate Change
MSC	Mesenchymal stem cells
NFR	Novel Food Regulations
OECD	Organisation for Economic Co-operation and Development
PDCAAS	Protein Digestibility-Corrected Amino Acid Score
QC	Quality Control
TGF-β	Transforming Growth Factor Beta
TUD	Technological University Dublin
UK	United Kingdom
USDA	United States Food and Drug Administration
USA	United States of America
VAT	Value Added Tax
WHO	World Health Organisation
WWF	World Wide Fund for Nature

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Chapter One: Introduction

1.1 Chapter Introduction

This chapter sets out to provide the reader with a general oversight and understanding of cultured meat. The definition, key terms and production process will be explained, as well as the history and origins of cultured meat. This chapter will focus on some of the key drivers for production of cultured meat, as well as introducing challenges faced by the industry in relation to commercialisation. Rationale is identified for this research topic and the research aims are outlined also.

1.1.1 Cultured Meat Overview

Cultured meat refers to meat which is produced using stem cells in an attempt to mimic conventional meat (Bhat, Kumar and Fayaz, 2015; Jairath, Mal, Gopinath and Singh, 2021). Essentially, it has the potential to be a substitute to that of conventional meat. Cultured meat may also be described as in vitro, lab-grown, synthetic or clean meat. Many researchers and governing bodies have identified and forecasted increased demand in meat and its consumption (Kumar et al. 2015). Various demographic factors have contributed to this such as, increase in population, increasing wealth and increasing consumption in developing countries (OECD/FAO., 2020; Gerber et al., 2013). This has caused concern and considerable strain among livestock production and processing systems in meeting these demands. This has been the main driver towards lab grown meat and will be discussed further at a later stage in this introduction.

Among the solutions, cultured meat has been highlighted as a potential sustainable alternative for consumers who may wish to be more responsible but do not wish to change the composition of their diet. Meat consumption has frequently been regarded as an important part of a healthy diet, as socially desirable and perhaps as an indicator of societal development (Bryant and Barnett, 2020). Whilst plant-based alternatives have been proposed, cultured meat and its constituents is an appealing alternate to those who still wish to include meat as part of their diet.

1.1.1.1 Cultured Meat Production

With regards to the process of producing cultured meat, the main aim is to recreate and grow the complex structure of livestock muscles with just a few starter cells. Whilst the general production method remains the same, some of the finer and more specific processes may vary. To begin, it is common that a biopsy is taken from a live animal which is then cut to liberate the stem cells as depicted in figure 1, which have the ability to proliferate but can also transform themselves into different types of cells, such as muscle cells and fat cells (Choi et al., 2020). Once these seed or starter cells have been obtained, they can be proliferated to achieve larger cell numbers (Bhat, Kumar and Fayaz, 2015). At a laboratory scale, flasks or dishes may be used. However, in order to perform this on a larger, more industrial scale, there is a need for bio-reactor systems (Post et al., 2020). Cells will divide and grow once they have been cultured in a suitable medium. The medium will provide the necessary nutrients to promote growth.

Some scholars have suggested that the best media contain fetal bovine serum (FBS), which is a serum made from the blood of a dead calf (Hawkes, 2015; van der Valk, 2018). However, it is not acceptable for vegetarians or vegans due to the nature of its origins. Whilst this is still commonly used, the industry has developed many new types of media which are suitable for this process, some of which are vegan friendly. These medias are further explored in the results and discussion section of this research.

As depicted in figure 1.1, once the appropriate number of cells has been grown/produced, cells may then be induced to differentiate into myotubes, adipocytes, or other mature cell types in muscle tissues (Zhang, 2020). Final cell maturity holds importance at this stage in the process as this will determine the nutritional value of the final product i.e. protein, fatty acids, vitamin content etc. (Liu, 2019). It is also noteworthy that whilst muscle stem cells tend to have strong myogenic differentiation potential, the diameter, length and protein content of ex vivo formed myofibers can differ considerably based on culture conditions and may be lower than that of real muscle fibers (Braga et al., 2017). Hence, much work is being done in the industry to optimise the differentiation stage based on the mechanism of in vivo muscle tissue development.

Finally, the cells produced are further processed into their desired product e.g., by moulding, colouring, addition of seasonings and in most cases, forming (Zhao et al., 2019). Considering cultured meat production is at its early stages in terms of commercialisation, most researchers have only been successful with forming a two-dimensional (2D) thin cell layer (Stephens et al., 2018). However, the moulding procedure can be merged into the differentiation step, where various cell types are co-cultured in a biomimetic three-dimensional (3D) environment provided and aided by a scaffold or hydrogel (Tuomisto, 2019). These advances in 3D bio-printing have been promising for the industry as a means of producing larger sized and more complex structures e.g. steaks and other whole muscle cuts (Kang et al., 2016).

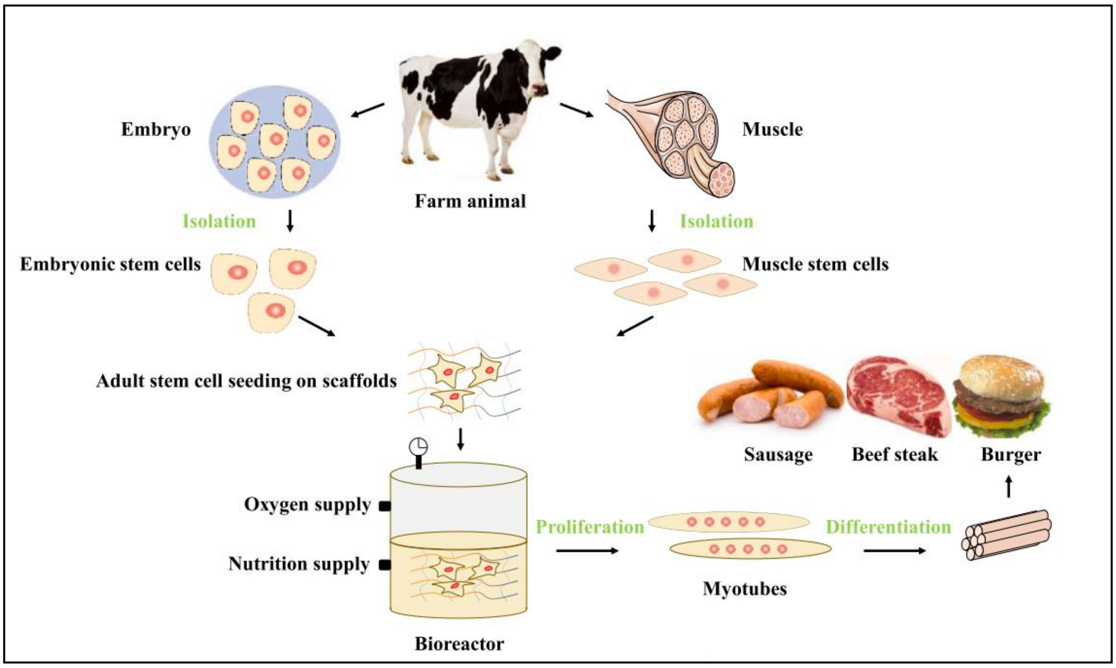

Figure 1.1. Diagram outlining a typical production process of cultured meat (taken from Zhang et al., 2020)

In order to provide an insight to the industrial process of cultured meat, figure 1.2 has been included which comprises various equipment pieces and provides an overview of the process flow. This figure mimics that of a monoclonal antibody production system for bovine myoblasts/Mesenchymal stem cells (MSC) expansion (Specht et al, 2018; Risner et al., 2020). It is noteworthy however, that this illustration provides a simple model. In reality, there are more complex steps within those outlined in figure 1.2.

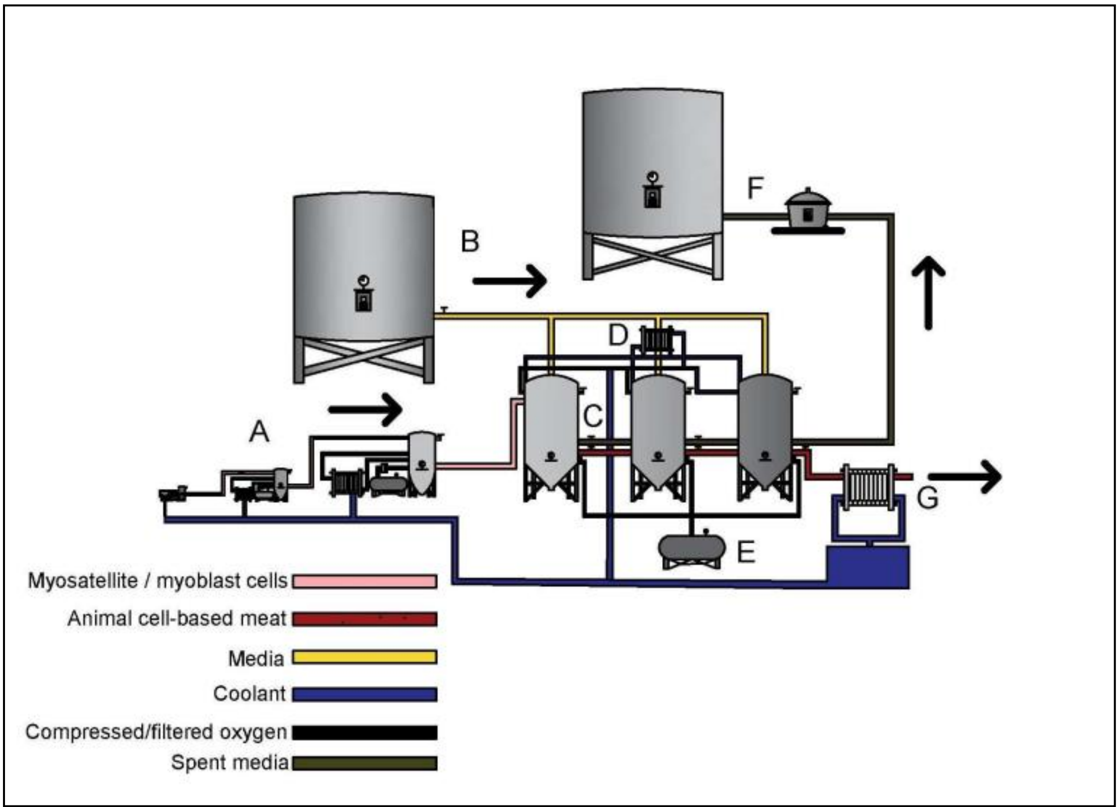

Figure 1.2. Illustration of processing steps of cultured meat production at factory scale. (Taken from Risner et al., 2020)

In summary, figure 1.2 illustrates the bioreactor seed train system (in part A), the media storage system (part B) and the continuous stir bioreactor system with unknown scaffolding processing occurring in bioreactor system (part C). Moreover, as can be seen from part D, the process includes a bioreactor temperature control system, an oxygen supply system (part E), media processing system (part F) and finally, the cooling system (part G).

1.1.2 History and Timeline of Cultured Meat

The beginning and evolution of cultured meat dates back as far as the early 20th century. Many studies note a memorable quote from Winston Churchill where he said, "Fifty years hence we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing by growing these parts separately under a suitable medium" (Sharma, Thind and Kaur, 2015). As depicted in figure 1.3, what was originally an idea or concept, flourished into an array of key developments throughout the next century with research and development continuing today. One of the most significant milestones was that of Professor Mark Post (Maastricht University) who with the financial support from Google co-founder, Sergey Brin, produced the world's first cultured beef burger, which was cooked and eaten at a London press conference in August 2013 (Hong et al., 2021).

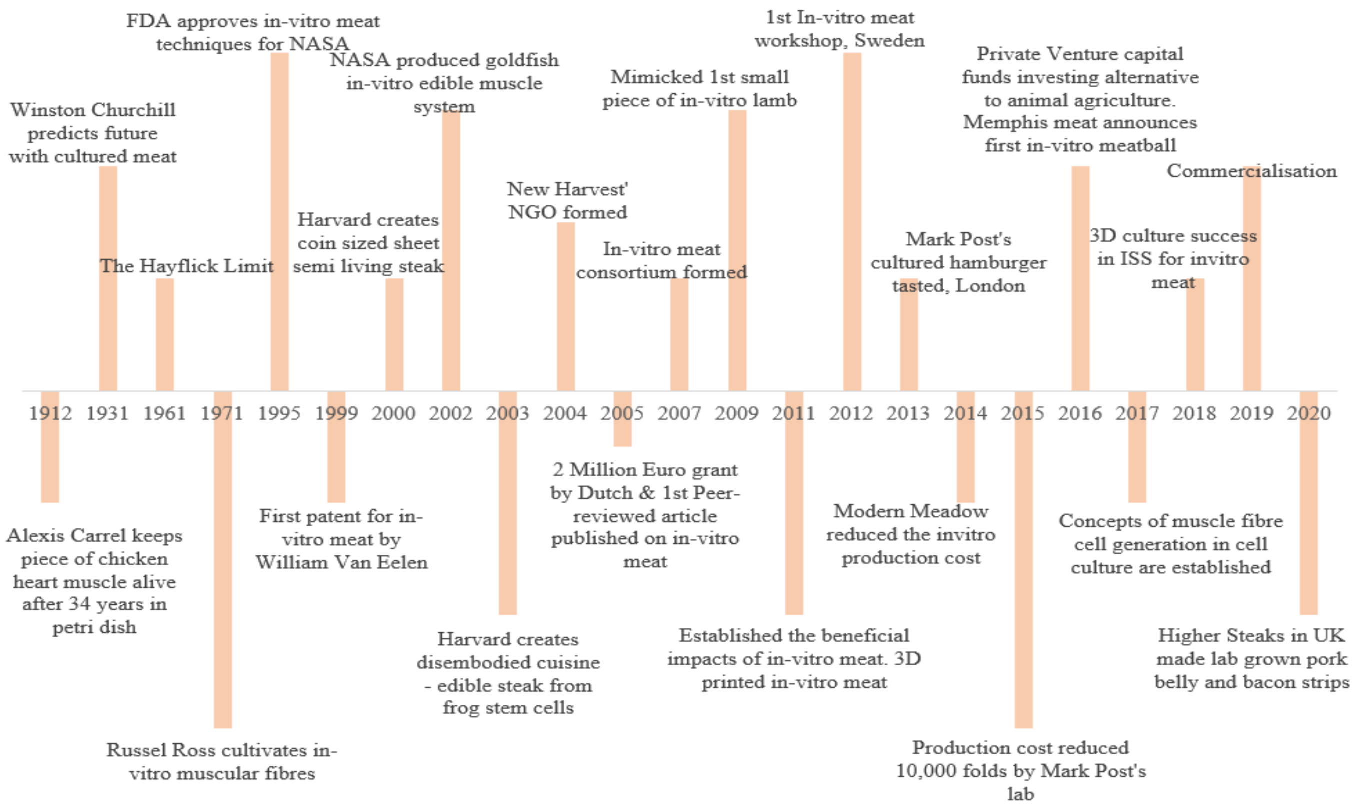

Figure 1.3: Overview of the timeline and associated milestones in the cultured meat industry (adapted from Guan et al., 2021; Hong et al., 2021).

As per figure 1.3, other significant milestones post 2013 included a cost reduction by 10,000 folds by Mark Post's lab and 3D culture success in 2018. This timeline of events provides a promising outlook on the future of cultured meat.

1.1.3 Drivers and Potential Benefits of Cultured Meat Consumption

1.1.3.1 Population and Growth

The availability of both safe and affordable protein is fundamental to human nutrition and food security. Food security has been defined by the Food and Agriculture Organization (FAO) as existing when 'all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy lifestyle' (FAO, 1996). Meat is an important source of high biological value protein, iron, vitamin B12 and some other B complex vitamins, as well as zinc, selenium and phosphorus (Pereira and Vicente, 2013). The protein intake recommendation established by the World Health Organisation (WHO) (2007) is 0.83 grams per kilogram of body weight per day. The growth of protein and red meat in the human diet over the last generation has delivered innumerable health and life benefits (Carbone and Pasiakos, 2019; Mitchell et al., 2017). Whilst plant-based proteins have become increasingly popular in recent years, there still remains a high demand for animal-based protein sources.

With a growing global population and thus, an increasing protein consumption, an exploration of alternative protein sources of food must be considered as a means of meeting global protein demand. Cultured meat has been suggested as a potential solution to food security concerns, particularly in relation to animal derived proteins. The world's population is estimated to increase to 11.2 billion by the year 2100. This will ultimately result in an increased consumption of meat, particularly in developing countries (Dupont & Fiebelkorn, 2020). A further estimation indicated that by 2050, animal products production would double, from 229 billion kilograms in 2000 for 6 billion people to 465 billion kilograms for 9.1 billion people (OECD/FAO, 2020).

In relation to meat, the FAO (2009) have hypothesized that the demand for meat will double from the year 2020 to 2050. Further estimates by Gerber et al (2013) have adjusted this forecast to state that this demand for meat will actually increase by up to 70% over the outlook period noted. This would present a huge challenge for livestock production and processing. Although livestock production systems help in fulfilling the demand for animal protein, meat production is a highly inefficient process which is taking a toll on the environment. These issues are discussed further in section 1.1.3.2

1.1.3.2 Sustainability and Climate Change

The topic of global warming and climate change has seen much light in the media and among governing bodies across the globe. Undeniably, the world must decrease emissions from agriculture and fossil fuels to halt global warming sufficiently. However, there is not one simple solution to this. This is a complex and sensitive topic which has been debated by scholars over the years. It is unreasonable and unrealistic to expect the global population to stop eating meat. This would also cause concern from a nutritional point of view based on the evidence presented in section 1.1.3.3. However, much can be done to minimise the effects of the agriculture and meat industry on the environment, one of which potential solutions may be meat cultivation.

A report by the Intergovernmental Panel on Climate Change (IPCC) (2019) indicated that up to 23% of the total greenhouse gas emissions (GHG) derive from agriculture, forestry and other land uses, which are among the major contributors to the global warming. Moreover, agricultural overexploitation, for example, larger farm and field sizes and an increased use of pesticides and fertilizers are also causing a loss of natural biodiversity and habitats (Geiger et al., 2010). Among agricultural practices, the livestock industry is also an important contributor to the global climate change, contributing between 12% and 18% to the total GHG emissions (González, Marquès, Nadal and Domingo, 2020). Several studies have alluded that cultured meat production can reduce emissions below that of conventional meat. However, some of these studies have been inconclusive and unrealistic, making it difficult to determine just how much more beneficial cultured meat is, in comparison to conventional meat for the environment.

Furthermore, a study by Sabaté et al. (2015) established the environmental costs of producing 1kg of protein from different plant and meat-based products. The results showed that production of 1 kg of protein from beef required 18 times more land, 10 times more water, 9 times more fuel, 12 times more fertilizer, and 10 times more pesticides than the same amount of protein obtained from kidney beans. Moreover, it was found that production of proteins from chicken or eggs also generates less waste than proteins from beef (Sabaté et al., 2015).

Considering the demand outlined in section 1.1.3.1, global livestock production is expected to increase by 14% (FAO, 2009). This may be supported by low feed prices and stable product prices ensuring remunerative profit margins to producers. Of this, poultry remains the fastest growing meat accounting for approximately one half of the projected increase in total meat output (OECD/FAO, 2020). It is worth mentioning that some have suggested that improvements in animal agriculture in relation to livestock intensification and animal welfare may help to alleviate food security, improve land use and address emission concerns (Grossi et al., 2018). High production intensities are associated with greater environmental efficiency. Whilst the industry has enjoyed some success in relation to moving towards more efficient livestock production, there have been concerned expressed which are linked to the impact of intensification on animal welfare.

1.1.3.3 Move away from animal-based protein consumption

In recent years, particularly in developed countries, there has been a move away from animal-based proteins and an upward trend in a plant-based diet. In an overall global dietary transition has seen meat consumption becoming associated with ‘perceived’ negative effects on health and environment (Cliceri et al., 2018). Sustainability has become a fundamental factor in the analysis of dietary patterns and guidelines around globally (Jones et al., 2016). The FAO (2012) define a sustainable diet as a ‘diet with low environmental impacts which contributes to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate**,** safe and healthy while optimizing natural and human resources.’

Correlation that meat, particularly red meat consumption has been linked to various health related illnesses such as cardiovascular disease, has been a major driver towards plant-based protein sources. (Feskens et al., 2013; Larsson and Orsini, 2013). However, it should be considered that those who consume are plant-based diet are more likely to be deficient in vitamin D, vitamin B12 and minerals such as, iodine, calcium, and zinc (Sakkas et al., 2020). Moreover, a high prevalence of up to 80% of vitamin B deficiency has been reported in Hong Kong and India, where vegans have been found to rarely use supplementation in their diets (Woo, Kwok and Celermajer, 2014).

Moreover, Berrazaga et al (2019) make that point that animal proteins are more digestible, have greater biological value, and protein digestibility-corrected amino acid score (PDCAAS) than plant-based proteins. This further provides motivation for a cultured meat market. Evidently, cultured meat may one such way of overcoming this issue as it can provide the nutrition that perhaps plant-based foods cannot, without potentially having the harsh effects on the environment that conventional meat production does. It has been suggested that cultured meat can be manipulated to have an increased nutritional value, for example, reduced fat (Warner, 2019). Although there are few studies to support this claim, it is a promising development in the field of cultured meat.

1.1.3.4 Animal Welfare Concerns

An enticing aspect of cultured meat production is that it has the potential to alleviate animal suffering. Animal welfare has long been a concern among activist groups who oppose animal slaughter. Whilst cultured meat production does involve the obtainment of cells via a biopsy method, there would still be a reduction in the overall number of slaughtered animals (Chriki and Hocquette, 2020). Moreover, some have referred to cultured meat as ‘victimless meat’ (Schaefer and Savulescu, 2014). Whilst this method of meat production may not be deemed strictly vegan and may not eradicate the slaughter of animals, it is a promising facilitator in the favour of cultured meat. With around 56 billion animals slaughtered yearly worldwide, cultured meat offers a promising reduction in such numbers (Ikei et al., 2014).

1.1.3.5 Food Safety

Food safety has been classed another key driver for cultured meat development and consumption. In general, there are several food safety concerns associated with meat. Many foodbourne pathogens such as campylobacter, Escherichia Coli and Salmonella are commonly found in meat and have been the cause of many foodbourne illnesses every year (Fegan and Jenson, 2018). Some argue that cultured meat may be free from microbial contamination due to it being produced without animals (Hong et al., 2021; Zhang et al., 2021). However, it is noteworthy that this is provided that conditions are sterile and that contamination in the culturing of meat process does not occur. Moreover, concerns around the topic of antibiotics, steroids and other growth promoters as a result of animal derived food products has had much media attention in recent years, sparking food safety concerns (Warner, 2019). This further enhances the argument for cultured meat as it has the potential to mitigate the use of such substances.

Additionally, other human affecting pathogens and diseases such as avian and swine influenza are prominent in livestock (particularly in intensive farming practices) (Hong et al., 2021). Cultured meat is therefore advantageous in relation to this issue as it would not only reduce the bacterial contamination and intensity of meat borne diseases (Jairath, Mal, Gopinath and Singh, 2021), but also lessen the use of pesticide and fungicide residues due to restricted and well controlled cell culturing environments (Bhat, Kumar and Bhat, 2015).

1.1.4 Challenges Associated with Cultured Meat

1.1.4.1 Consumer Acceptance

Several studies have been conducted to identify the willingness of consumers to consume cultured meat. It is noteworthy that results of these studies varied and were conflicting (Bryant & Barnett, 2020; Hocquette et al., 2015; Slade, 2018; Wilks & Phillips, 2017). Such discrepancies, however, may be due to various factors such as, question design, descriptions of cultured meat used and differences in the samples, for example, demographic factors. A study by Wilks and Phillips (2017) showed differences in opinion relating to demographics e.g. liberals (vs. conservatives), low-income participants versus high-income respondents, and males, as opposed to females were more willing to try cultured meat. Moreover, this study highlighted that whilst vegetarians and vegans had a more positive view of some aspects of cultured meat, they were less inclined to eat it than omnivores. Additionally, findings by Slade (2018) indicated that males had a greater preference for cultured meat as opposed to females and that younger and more educated respondents also preferred cultured meat.

Some of the more negative results indicated that the opposition to cultured meat by consumers was generally associated with perception of unnaturalness, food safety concerns, healthiness, taste, texture, and price (Wilks & Phillips, 2017). Further to this, Marcu et al. (2015) reported that ‘natural’ versus ‘artificial’ was one of the responses to determine the perception of cultured meat in comparison with conventional meat. This is supported by a study carried out by Laestadius and Caldwell (2015). Whilst this research does not attempt to identify consumer perception of cultured meat, it is important to consider the view of the consumer, as this will ultimately determine the survivability of a new product in the market. Of course, it is imperative that cultured meat be affordable, sustainable and able to meet market demand, however consumers hold the most importance in the market, as success is reliant on the consumer making the purchase.

1.1.4.2 Technical Challenges

There are several technical challenges associated with cultured meat production which have caused difficulty in the feasibility and scalability of its production. Moreover, some of these difficulties have contributed to the cost of production of cultured meat which continues to be a problem in the industry. These challenges are debated further in the results and discussion sections, however, this section provides and introduction to relevant technical issues.

One significant challenge highlighted by scholars and industry experts is the selection of a suitable cell line which has infinite self-renewal capacity and functional immortalisation (Hocquette, 2016). It has been suggested that embryonic stem cells are suitable due to their self-renewal capacity, however, it should be considered that over time, gene mutations may occur which limits their use (Jairath et al., 2021). During the process of cell culturing, cancerous cells may be produced and potentially not identified by processors which has caused concern in the industry (Hocquette, 2016). However, it is unlikely that such cells would cause harm to humans on consumption as they are killed by cooking. This is still an important consideration as it may be a sensitive topic for consumers.

Secondly, there are challenges presented relating to the culture medium, such as, the component costs and component characteristics which may affect the production capabilities and the cultured meat product's organoleptic properties (van der Valk., 2018). Details of these challenges are analysed in the results and discussion section. Moreover, industry experts and researchers have experienced challenges in the scaling up of production, relating to equipment and process design. Studies have shown very high capital costs for equipment and buildings, such as bioreactor costs (Humbird, 2020; CE Delft, 2021). Other cost considerations include water usage, electricity costs, labour and general maintenance, among other expenses. Costs and technicalities are considered in detail in the results and discussion section.

1.1.4.3 Sensory Attributes

A further barrier is the challenge of producing cultured meat with similar organoleptic properties to that of conventional meat. In its natural state, cultured meat tends to be colourless (Bhat et al., 2019), which clearly differs from conventional meat's colouring. Likewise, difficulty reproducing the same meat taste has been encountered in cultured meat production (Hocquette, 2016). Whist the industry has had success in producing processed meat products, there has been less progress made in the production of whole muscle cuts due to the increased complexity of this process (Balasubramanian et al., 2021). In order to produce cultured meat with more similar sensory characteristics to conventional meat, edible scaffolding may be used together with tissue engineering and regenerative medicine techniques (Tomiyama et al., 2020). Scaffolds with striated textures that imitate the fundamental structure of muscle have been shown to promote myotube formation (Ostrovidov et al., 2014). In addition, a considerable challenge in the production of competitive cultured meat is to ensure that the necessary nutrients are present, as briefly mentioned in section 1.1.3.3.

1.2 Rationale

This introduction has outlined some of the key factors in support of cultured meat. Cultured meat has been vastly explored as a solution of food security concerns in relation to protein and meat requirements of the growing population. Cultured meat has the potential to reduce the need for intensive animal farming and processing, which in turn can potentially reduce the negative impact the industry is having on the environment. However, studies have outlined concern in relation to the viability of cultured meat production. Whilst there have been successful efforts in the production of cultured meat with satisfactory organoleptic properties and which have been deemed safe from a microbiological point of view (Balasubramanian et al., 2021; Melzener et al., 2020; Hong et al., 2021), these efforts have not been without substantial costs. The materials required for cultured meat, combined with the cost of production, as previously noted, have heavily contributed to the expense of producing cultured meat.

A media event involving Mark Post in 2013 holds much significance, where a $325,000 (€250,000) cultivated hamburger was presented to a panel of food critics in London. While this was a key milestone in the cultured meat industry, there figure presented was clearly an unsustainable one. It is notable that this figure included major direct costs, including that of the researchers and scientists who were working on this project. In 2015 however, Post presented a more promising cost estimate of $65/kg of cultured meat. Much work has been done in the industry to bring scalability to such a level that this target can be met, with development still continuing today. Such costs have provided a sound basis for this research in order to identify their derivation and to establish cost effective solutions.

1.3 Aims and Research Questions

Ultimately this research question asks whether or not cultured meat is economically viable. Thus, the following aims have been outlined:

- Establish the current state of the industry in terms of commercialisation and going to market.
- To find out if cultured meat is a cost-effective solution to global protein demand and as an alternative to conventional meat.
- To identify key areas where costs stem from and explore methods for reducing costs/making cultured meat more viable.
- Forecast the potential retail cost for consumers and identify cost goals of cultured meat researchers and experts. This research will further explore achievability of such costs.

- Consider potential taxes on meat in relation to environmental concerns and establish if cultured meat could be a viable alternative to avoiding such taxes.
- Carry out a comparison with conventional meat in relation to farming practices, herd numbers, processing costs and final retail costs.

1.4 Chapter Conclusion

Chapter 1 provides a summary of the history of cultured meat, as well as outlining the many factors and key reasons for pursuing its development. Whilst there are still many challenges for the cultured meat industry to overcome, there have been promising developments over the past century in the way of bringing cultured meat to market. The following chapters will outline and further detail these key challenges from an economic and general technical feasibility perspective and the associated methodology employed in doing so.

Chapter Two: Methodology

2.1 Chapter Introduction

Having established the theoretical and academic background underpinning this study in Chapter One, the methodology of the research shall now be outlined. Ethical approval was granted by Technological University Dublin (TUD) prior to the commencement of this study. There was no primary research aspect of this study.

2.2 Methods: Study Design

This section outlines the methods used to assess the economic viability of cultured meat. The research method used has been a desk-based study of, peer reviewed, published research papers along with data from government and non-governmental organisation sources. This methods section shows how results on current market status of cultured meat was established. It further shows the methods employed when searching databases for relevant research on the costs and other technoeconomic challenges associated with cultured meat production, particularly the up-scaling of cultured meat production. As outlined in chapter 1, a number of studies have shown the benefits which cultured meat can have if successfully brought to market in relation to food security, environmental improvements, potential health benefits and increased food safety for the consumer. However, these studies have failed to acknowledge some of the key barriers standing in the way of cultured meat commercialisation.

2.3 Scope

The scope of this research question focuses on the technoeconomic challenges of bring cultured meat to the marketplace. This research establishes where the industry is currently in relation to getting to market. Focus will be placed on current companies operating in this field, various species of meat being explored, geographical location and progress to date. The scope of this research is to highlight specific areas of concern which are driving up the cost of cultured meat production and ultimately pinpoint areas where savings can be made. This research will use current literature to establish exact costs and associated cost reductions if changes are made to processes and formulations. Some of the key areas that this research focuses on, due to frequent reporting in literature are cell source, media formulation, bioreactors, production timings and retail costs. Finally, the scope of this research will also include a comparison of cultured meat with conventional meat.

2.4 Literature Search Methods

A range of databases that present reputable peer reviewed published literature were used when searching for literature such as:

- Web of Science
- Science direct
- Pubmed
- Scopus

The TUD online library was also utilised for searches. Grey literature was also searched and some publications were used such as, World Health Organisation (WHO) and the FAO. Publications by these types of reputable organisations were deemed acceptable for use in this research. Databases such as those on the world wide web, for example, Wikipedia, were completely avoided as these are unreliable information sources. Key words relating to this subject area and the aims of this research were used to identify and select appropriate papers.

The following key words such as were used;

- Cultured meat, CM, lab grown meat, clean meat, in vitro meat, cell-based meat, laboratory grown meat and cultivated meat.

Some more specific terms were also searched, such as;

- Viability of cultured meat, economics of cultured meat, economic viability of cultured meat, cost of cultured meat and feasibility of cultured meat.

If there were too many hits, or papers using a search word, the word "AND" was used to limit the search criteria. Likewise, if the specific terms did not return a substantial number of papers, the word 'AND' was used. For example:

- Cultured meat 'AND' Economics, Cultured Meat 'AND' Viability

The use of the word ‘AND’ means that literature that including information on both these terms was presented. If not enough literature was returned in the search, the word “OR” was used to expand the literature found. For example:

- Cultured Meat ‘OR’ Lab Grown Meat, Cultured Meat ‘OR’ Cultured Meat viability etc.

The use of the word ‘OR’ produced literature for both these search terms. Inverted commas were also used to limit the search.

- “Cultured meat” and “Cultured Meat viability”, “Cultured meat” and “Cultured Meat Economics” etc.

2.4.1 Eligibility Criteria

For the articles to be included in this review it they were required to meet the following criteria;

- Were published in the last 20 years
- Were written in the English language
- Had their full text available
- Quality of data in the papers was high and material was relevant to the research question

After performing the search, the following methods were applied. The title of each paper under the search was scanned and read. If it appeared to be relevant, the abstract was also analysed to determine suitability of the paper. If the papers contained relevant information to the research question, then the papers were kept and used. Data which was included was predominantly published within the last five years. Any data used, which was solder than this, has only been used where the data is still current and relevant or where no new data has been generated.

2.4.2 Exclusion Criteria

Non peer reviewed data has been excluded for review data. Unsubstantiated data has also been excluded from the review. Of this, there was one exception in the use of non-peer reviewed data. Use of a google search was utilised for one aspect of this research and is outlined in the next section. Whilst some searches of cultured meat returned results in relation to growth of human cells, such papers were excluded due to their irrelevance to the topic and ties with the medical industry.

2.4.3 Non Peer Reviewed Data

In order to establish what companies were out there in the cultured meat sector, a google search was performed using the following search terms:

- 'List of Cultured meat companies'
- 'Number of cultured meat companies'
- 'cultured meat company list'
- 'lab grown meat companies'.

The 'List of cultured meat companies' term was successful and returned a result of a website called 'Pivot Foods' (Pivot Food Investment, 2021). This provided a list of companies with their associated description including founding year, type of meat and country. A filter available on the website was used to remove products which were not applicable. Filters which were selected were product type, from which 'meat,' 'beef,' 'chicken,' 'pork,' 'pet food' and 'seafood' were selected. These companies were further validated using a 'State of the Industry Report' obtained from Good Food Institute (GFI) (2020)

2.4.3.1 Company Inclusion Criteria

Companies shown after the filter was applied and were categorised in the 'meat' 'Beef' 'chicken' 'pork' 'seafood' and 'petfood' were included for the purpose of this research.

2.4.3.2 Company Exclusion Criteria

This website returned some unapplicable companies, such as those producing cultured dairy products. For the purpose of this study, these companies were excluded.

2.4.3.3 Validation of Companies

Each company was checked against the list provided by the Good Food Institute (2020) for validation purposes. Each company on the list was further validated by use of a further google search to establish if the company had a website. This was particularly relevant to companies who were not listed in the Good Food Institute (2020) report. A google search was also used with the terms noted in section 2.4.3 to identify any additional cultured meat companies which had not been noted on the Pivot foods website. Google was only used up to page 4 on the search engine in order to keep the specify and narrow down the search. Note that there were no further companies identified by this means.

Chapter 3: Results

3.1 Current Status of Cultured Meat Commercialisation

3.1.1 Literature Results

As depicted in figure 3.1, as of May 2020 it is evident that of those companies who have specifically declared the species being produced, there is at least 25% are focused on beef production, 22% on cultured poultry, such as chicken and duck, and 19% which are focused on pork and a further 19% centred on cultured seafood (such as fish and shrimp). In addition, there are two companies exploring mouse meat (an alternative pet food) and one company each for kangaroo and horse meat (Choudhury et al., 2020).

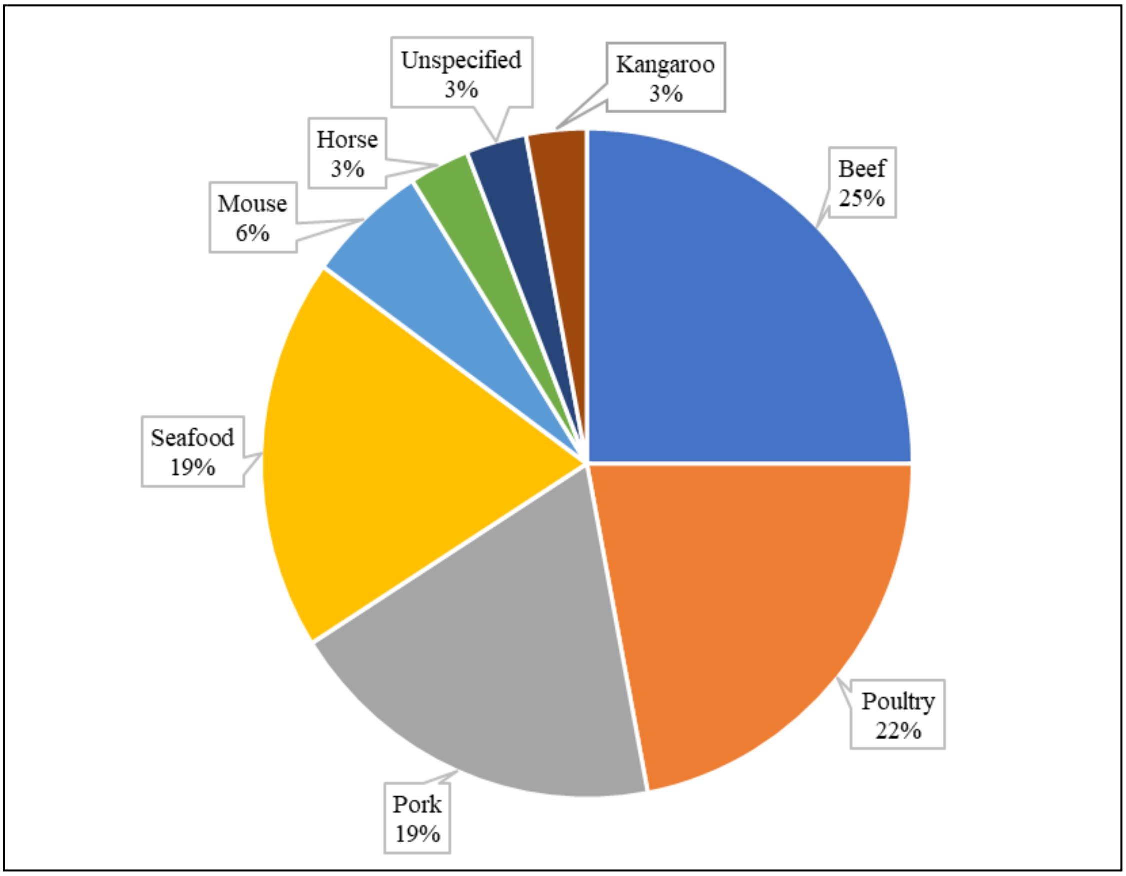

Figure 3.1. Type of species being developed by cultured meat companies (adapted from Choudhury et al., 2020).

The Good Food Institute provide slightly different figures and have reported 28% of cultured meat companies are interested in cultured beef and pork, while 12% are interested in seafood, 10% in poultry, and 28% in raw materials or equipment used in the production process. This concurs with figures provided by Crosser et al (2020) and Shaikh et al (2021). Moreover, geographic location of cultured meat companies is varied. Figure 3.2 provides and overview of companies who are operating in the cultured meat market and their headquartering country. As per figure 3.2, Choudhury et al (2020) indicate that 40% of companies captured are based in North America. The rest of the companies are based in Asia (31%), Europe (25%) and Australia respectively.

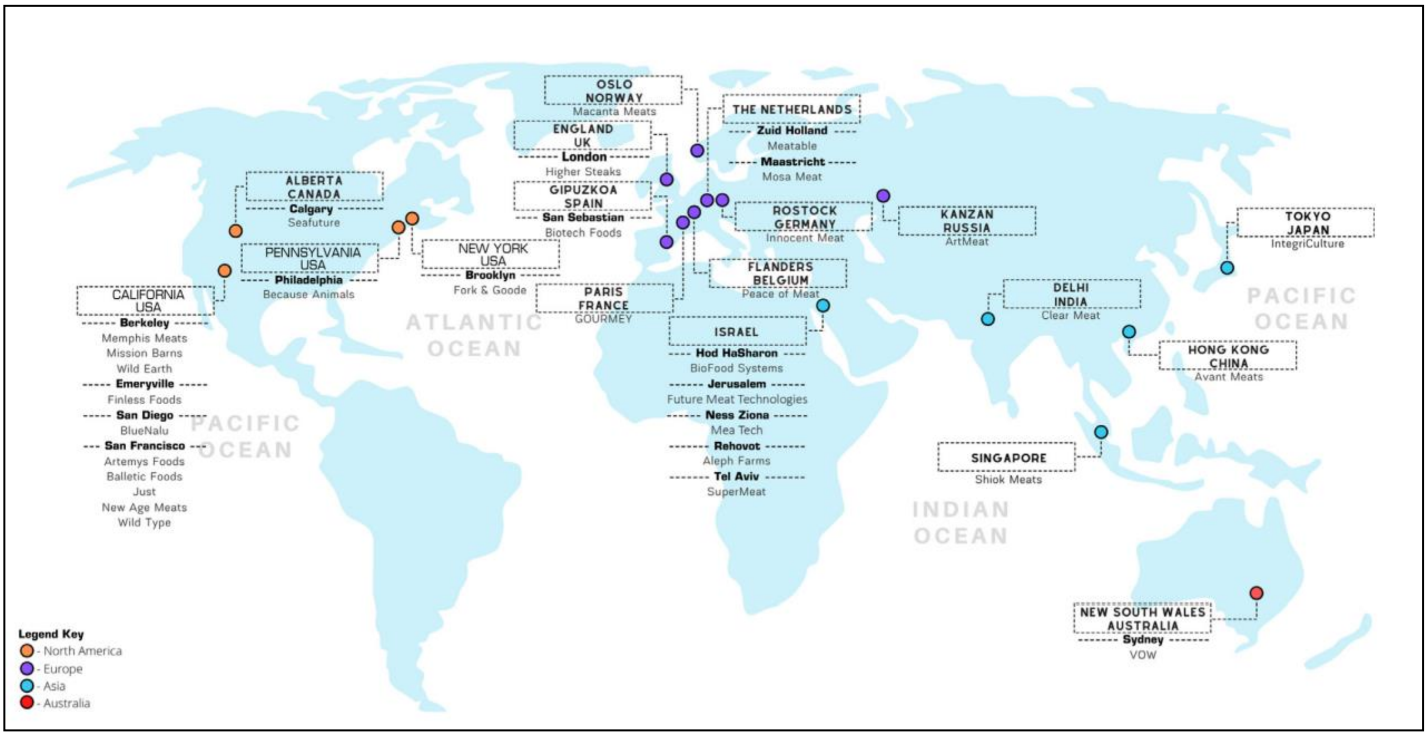

Figure 3.2. Geographical location of companies operating in the cultured meat industry (Taken from the Good Food Institute, 2020).

Figures from a report by the Good Food Institute (2020) indicate that by the end of 2020, there are approximately 60 early-stage companies in the cultured meat industry. This study also showed that over half of these companies were established and launched from 2018 onwards (Crosser et al., 2020). According to this report, the companies operating in the cultured meat industry are based in 19 different countries and 5 different continents. The report indicates that 37% are located in North America, 25% in Asia, and 21% in Europe.

Furthermore, the Good Food Institute (2020) indicates that there was an estimated over $460 million invested in cultured meat companies between 2016 and 2020. Over 75% ($350 million) was invested in the years 2019 and 2020. It is further reported that Memphis Meat has raised nearly $200 million, while Mosa Meat has raised over $85 million. It is notable that products being developed are those which would be described in the meat industry as 'further processed,' e.g. chicken nuggets and burgers, as depicted in table 3.1. These types of products have been deemed by researchers as the most suitable cultured meat products at the early stages of cultured meat production. This is analysed further in the discussion section.

Table 3.1: Examples of diverse cultured meat products currently being developed (adapted from Hong et al., 2021)

Species	Company	Product	Manufacture Year	Country
Chicken Meat	Just	Chicken Nugget	2019	USA
	Memphis Meats	Chicken Tender	2017	USA
	Peace of Meat	Chicken Nugget	2020	Belgium
	Future Meat Technologies	Shawarma	2019	Israel
Duck Meat	JUST	Duck pâte	2020	USA
	Memphis Meats	Nugget	2019	USA
	Gourmey	Fois Gras	2020	France
Beef	Mosa Meat	Burger	2013	Netherlands
	Memphis Meats	Meatball	2016	USA
Pork	Higher Steaks	Pork Belly and Bacon	2020	UK
	New Age Meats	Pork Sausage	2019	USA

3.1.2 Search Results

The primary search for companies in currently operating in the cultured meat industry returned a result of 53 companies (based on the following species: beef, poultry, pork, seafood, mouse, kangaroo and petfood). Geographical location of these companies was obtained and it was found that the United States of America (USA) had the highest number of cultured meat companies (16) as represented in figure 3.3. This was followed by Israel who currently have 5 cultured meat companies, then Singapore, China, Germany and the United Kingdom (UK) who each have 3. Raw data is available in Appendix 1. Moreover, other notable findings from this search showed that over 22% of the companies currently in the sector were founded from 2020 onwards. 45% of these companies were founded after 2019.

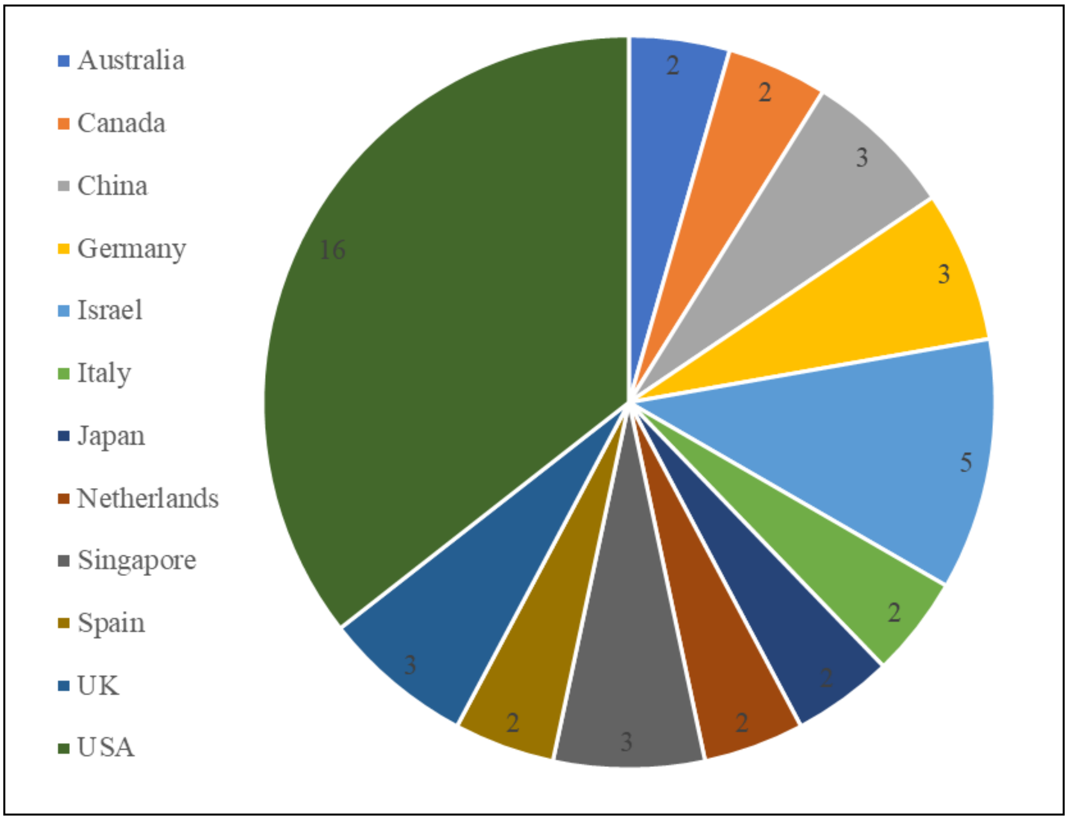

Figure 3.3. Outline of top 12 countries of headquarter for cultured meat companies.

3.1.3 Regulation

As per section 3.1.1 and 3.1.2, there is evidently much work being done to upscale cultured meat production and bring it to market. Several companies are working on different cultured meat products, however, it must be noted that their sale will be subject to regulatory approval. Governing and regulatory bodies vary country to country and some have already made steps towards approving cultured meat for sale. This section attempts to summarise the status of regulation in different locations.

The most significant progress has been seen in Singapore, where Eat Just secured regulatory approval for the sale of cultivated chicken (Oxford Economics, 2021). Melzener et al (2020) have suggested that will make its way to the market in the European Union (EU) under the Novel Food Regulations (NFR) (Regulation (EC) No 2015/2283). The European Food Safety Authority's (EFSA) regulation on novel foods is applicable to cultured meat and outlines a process of approximately eighteen months whereby a company has the opportunity to provide evidence of the safety of the product (Melzener et al., 2020). Furthermore, some scholars suggest that additional regulations and inspection practices may need to be added to the existing frameworks for the cultured meat industry (Iyer and Iyer, 2020; Melzener et al., 2020). Nonetheless, authorisation will be required prior to its sale to ensure that it is safe for human consumption.

In 2019 the US Food and Drug Administration (FDA) and the US Department of Agriculture's (USDA) Food Safety and Inspection Service established a formal agreement on how regulatory tools would be used to help ensure that foods comprising of or containing cultured animal cells entering the US market were safe and properly labelled. This agreement also outlined the parts of the process which each agency would take responsibility for and oversee. This was deemed a significant step in developing a framework and providing clarity to those operating in the cultured meat sectors on producing, distributing and sale of such foods in the USA (Food Made with Cultured Animal Cells, 2021). To the knowledge of the author at the time of writing, there has been no regulatory approval of any cultured meat product in the USA or EU to date. Results on regulatory status of cultured meat in other geographical locations such as parts of Asia and Africa could not be obtained. This was due a lack of literature available in the English language.

3.2 Economical Considerations and Costs

Whilst this study attempts to make estimates in line of costs to produce cultured meat, it should be considered that there are several variables which may fluctuate. Such fluctuations may be due to costs related to geographical location of the manufacturing facility, seasonality, volatility of some commodities, exact process being employed, among other factors. Figure 3.4 illustrates the key technological factors which can contribute to cost of production of cultured meat. Such factors include maturation time, fibroblast growth factor 2 (FGF-2) concentration and costs, glucose concentration, glucose consumption rates, oxygen consumption rate and transforming growth factor beta (TGF-β) and cell-based components (e.g. average cell volume and density) (Risner et al., 2020).

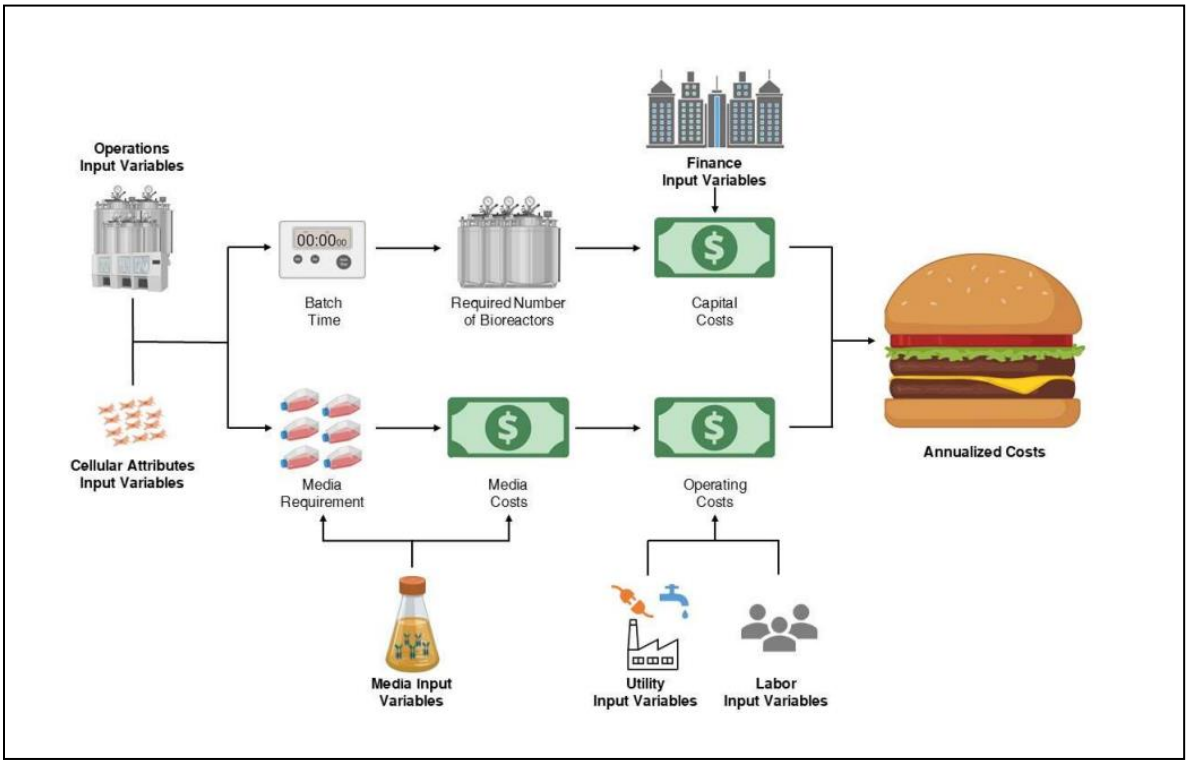

Figure 3.4. Economic flow diagram of the cultured meat process (grouped into categories which include operations, cellular attributes, finance, media, utility and labour) (Taken from Risner et al., 2020).

3.2.1 Cell Source

As briefly mentioned in the introduction section, a key challenge within the cultured meat industry is the selection of an appropriate cell source for the animal tissue culture (Arshad et al., 2017: Post, 2012). Whilst several studies have attempted to address this issue, the main challenges which has been established, is obtaining a sufficient number of homogeneous starter cells for the proliferation and differentiation phase to be effective (Arshad et al., 2017). Although the cell source is not directly linked to the production cost, it indirectly impacts the efficiency of the process and so, has been given consideration as part of this research. There are two main ways in which cell lines can be formed. One method is by induction where genetic or chemical engineering is used to program the cells to proliferate (Stephens et al., 2018) or by the selection of spontaneous mutations where the cell can express immortality and further culture the resulting population (Ramboer et al., 2014). However, this can cause some difficulty and complications and is discussed further in section 4.3.1. The second option is to primarily harvest the cells from the native tissues, i.e. from the animal or heard of animals. This would occur on an intermittent basis and would be subsequently cultured once extracted (Stephens et al., 2018).

Moreover, studies have shown that the animal which is the stem cell donor can have a significant effect on the efficiency of the cultured meat process (Post, 2012, Shaikh et al., 2021). Animal characteristics are further explored in the discussion section. Two considerations in relation to this issue have been highlighted, the optimisation for the yield of stem cells per mass of tissue and the optimisation of the longevity of stem cells (the number of populations they can undergo, while still retaining the ability to differentiate to form mature tissue for meat production) (Melzener et al, 2020). Collectively, these factors will determine the multiplicity factory (specifically the mass of the cultured meat that can be produced from a given mass of starting tissue (Choi et al., 2020; Stephens et al., 2018). Timings of growth associated with such factors are detailed further in section 3.2.4 timings.

3.2.2 Media

All studies examined used media as the growth platform for cultured meat. Various studies attempted to identify potential costs of media and more so, scaled up costs of media at bulk levels. This research found that there are a number of companies who are operating in media production and are currently working on development and improvement of media for lab grown meat. Some of the companies operating in this field include Biftek, Cellivate Technologies, Future Fields, Heuros, Multus Media among many others (Good Food Institute, 2020). Several industry experts and scholars note that the medium for culturing cells will provide the highest marginal cost contribution at an industrial scale. It is estimated that the cost of the medium in terms of the overall product cost will range between 55% and 95% (Humbird, 2020; Risner, 2020; Specht, 2020).

Originally, Fetal Bovine Serum (FBS) was the component of choice in relation to growth mediums. FBS showed great success in cultured mammalian cell lines and in the biopharmaceutical industry also (Van der Valk et al., 2010). FBS is harvested from bovine foetuses and can be taken from pregnant cows during slaughter (van Der Valk et al., 2018). It contains a large number of components, like growth factors, proteins, vitamins, trace elements, hormones, etc., essential for the growth and maintenance of cells (Schiff, 2005). Moreover, FBS is often harvested by a cardiac puncture method, frequently without any form of anaesthesia (Hawkes, 2015) which presents animal welfare concerns. As a result, in recent years, the use of FBS has been somewhat condemned within the biomanufacturing industry and the industry has seen a move away from its use. Among the papers reviewed as part of this research, models presented (published within the last 8 years) did not utilise FBS within the media formulatio (Humbird, 2020; Risner, 2020; Tramper and Van der Wheel, 2014; Specht 2020). From an economical perspective, FBS is also deemed too expensive to efficiently utilise for cultured meat, even in large scale production (van Der Valk et alk., 2018). The use of FBS is debated further in the discussion section.

Whilst likely due to competitive reasons, companies do not disclose exact ingredients and quantities used in media, some scholars, such as Humbird (2020) and Specht (2020) have attempted to model formulations and perform costings. Typically, an industry standard for the amount of growth media required for cell cultivation is between 10 and 20% (Stephens et al., 2018). Generically, the industry highlights key starting components which will form part of the media formulation. These components or ingredients include a single substrate (usually a sugar) for carbon and energy, a single inorganic nitrogen source (ammonia or nitrate salt), a small amount of phosphate, and very small amounts of sulphur and trace metals (Humbird, 2020). In addition, culturing of meat cells requires a combination of amino acids in order to meet the cells' nitrogen demand (Ramani et al., 2021). Additionally, if the cell source is stem cells, then other components may be used in the media such as, horemones, vitamin and cytokines (Humbird, 2021). These components are often referred to as growth factors.

Table 3.2: An overview of the amount of macronutrients (Glucose, EAA's and NAA's) required in a 100kTa cell mass production per gram of wet mas, demand at scale (kTa), current production volume (kTa), estimated price per component and overall cost contribution to cell mass ($/kg) (Adapted from Humbird, 2020).

Component		**Demand (g/g wet)**	**Demand at scale (kTa)**	**Current Volume (kTA)**	**Est. price at scale ($/kg)**	**Contrib. to cell mass ($/kg wet)**
Glucose		0.362	36.2	4000	0.26	**0.10**
Essential Amino Acids (EAA's)	L-arginine	0.016	1.6	1.5	70	1.12
	L-cysteine	0.005	0.5	10	137	0.67
	L-glutamine	0.044	4.4	3	40	1.74
	L-histidine	0.006	0.6	0.4	118	0.75
	L-isoleucine	0.012	1.2	0.4	83	0.98
	L-lysine	0.02	2	2317	62	1.23
	L-methionine	0.004	0.4	1172	156	0.6
	L-phenylalanine	0.011	1.1	30	85	0.96
	L-threonine	0.014	1.4	684	76	1.05
	L-tryptophan	0.004	0.4	14	146	0.64
	L-tyrosine	0.012	1.2	0.2	81	1
	L-valine	0.016	1.6	2	71	1.11
Total EAA						**11.84**
Non-essential Amino Acids (NAA's)	L-alanine	0.016	1.6	1.2	71	1.11
	L-asparagine	0.011	1.1	0.1	85	0.96
	L-aspartic acid	0.014	1.4	10	75	1.06
	L-glutamic acidc	-	-	145	-	-
	Glycine	0.011	1.1	23	87	0.95
	L-leucine	0.019	1.9	0.5	63	1.21
	L-proline	0.01	1	0.4	90	0.92
	L-serine	0.015	1.5	0.2	74	1.07
Total NAA						**7.29**
Total Macronutrients						**19.23**

*Note that these prices are based on average costs in the United States of America.

As depicted in Table 3.2, amino acids clearly have a significant contribution to the overall macronutrient cost of the media ($19.23 per kg/wet to be exact). It is noteworthy that studies have shown that amino acids which tend to have smaller market volumes have a higher cost. This is represented by figure 3.5 which gives examples of amino acids, their availability and their cost. It is notable that suitably pure formulations cost more (Humbird, 2020).

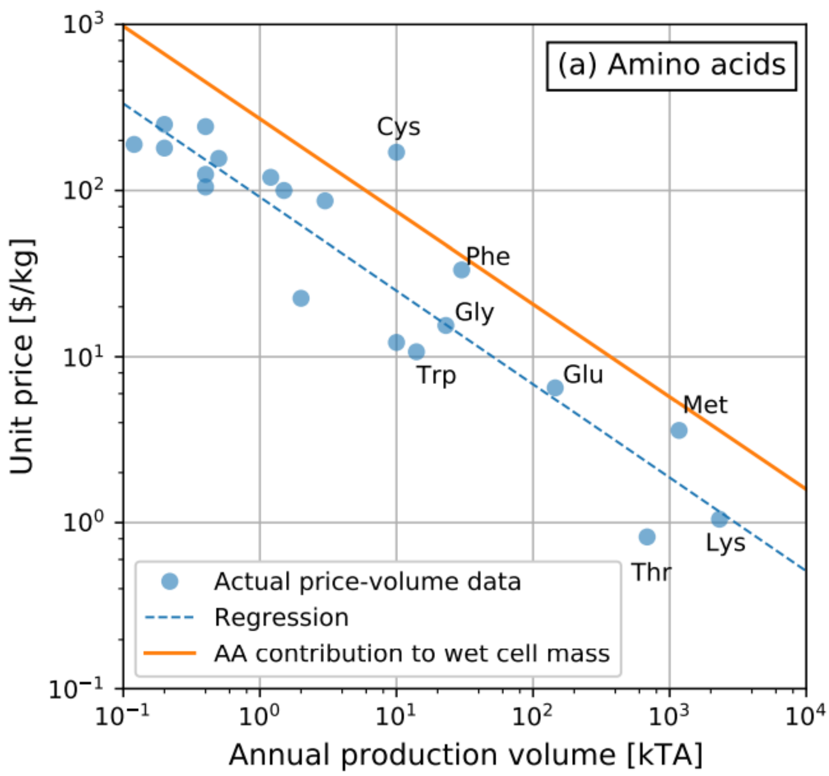

Figure 3.5: An example of annual production volume of some amino acids versus unit price.

Plant protein hydrolysate, in particular Soybean hydrolysate, has been identified as a potential alternative to amino acids. However, studies relating suitability of plant protein hydrolysate have been inconclusive and have demonstrated that it may only be beneficial in small amounts (Swartz, 2021). As per figure 3.6, it is evident that soybean lacks L-glutamine and L-tyrosine which is one shortcoming of its use. Further factors influencing suitability are considered in the discussion section of this research. Humbird (2020) models its use considering that current soybean meal pricing for animal feed was approximately $0.33 per kilogram. Table 3.3 highlights this model and includes a costing of additional L-glutamine and L-tryosine to account for the lack of these amino acids in the soybean. Whilst soy hydrolysate may seem like a promising alternative from an economical perspective, it is notable that soy production can have negative impacts on the environment.

Since soy is a plant, with increased demand and consumption comes increased land use, deforestation and subsequently, a loss of biodiversity (Sun et al., 2018). Majority of the world's soy production occurs in South America (Gil, 2020). An area known as the Cerrado, in Brazil holds approximately 5% of the world's biodiversity and is one of South America's most important water sources. However, over the past forty years, approximately half of this area has been converted for agricultural purposes and pastures, of which soy cultivation now makes up around 7% of the Cerrado (World Wide Fund for Nature (WWF), 2014). This 7% area is the equivalent of the size of England. It is estimated that between 2001 and 2010, around 4 million hectares of forest were destroyed annually in South America, primarily for soy and beef production (World Wide Fund for Nature (WWF), 2014). Moreover, much of the harvested soy is exported to Europe which further impacts the carbon footprint of soy.

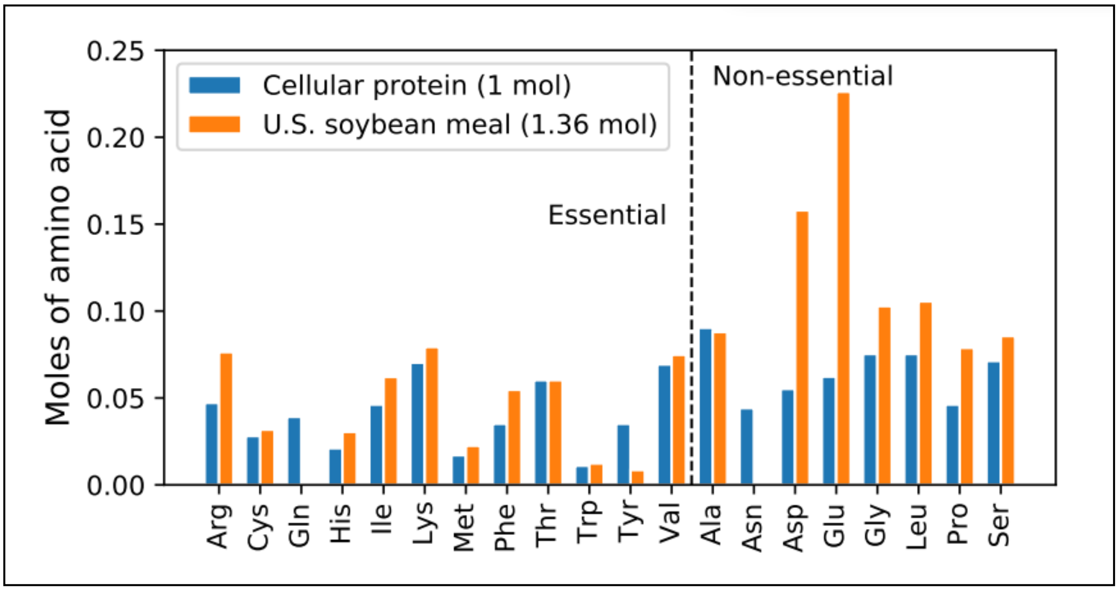

Figure 3.6: Amino-acid profile of cellular protein and soybean meal (taken from Humbird, 2020).

As depicted in table 3.3, if researchers and producers could make this formula effective, a new raw material price can be calculated as just under $3.40/kg total cell mass. This cost reduction of total macronutrients from $19.23 to $3.39 represents a decrease of approximately 82%. It should be considered however, that this is still only considering the costs of macronutrients. There are various other micronutrients which will have a contribution to the overall cost.

Table 3.3: Costing of Hydrolysate and supplemental amino acid demands and costs at 100 kTA cell mass production.

Component		Demand (g/g wet)	Demand at scale (kTa)	Est. price at scale ($/kg)	Contrib. to cell mass ($/kg wet)
Glucose		0.362	36.2	0.26	**0.10**
Soy hydrolysate		0.337	33.7	2	0.67
Supplemental Amino Acids	L-glutamine	0.044	4.4	40	1.74
	L-tyrosine	0.009	0.9	95	0.88
Total Macronutrients					**3.39**

A similar model has been hypothesised by Specht (2020) which outlines multiple scenarios to ultimately determine potential costs of media per kilogram of meat produced. Specht's findings concur, to a degree with that of Humbird, however, there was some variation in media formulation. Table 3.4 below presents a baseline scenario (or perhaps more applicable, a worst-case scenario) of the cost per litre of media for a 20,000L batch.

Table 3.4: Cost of 8 key components for model medium and relative cost contribution to a hypothetic 20,000 litre batch (adapted from Specht 2020).

Components	Final Concentration (mg/L)	Amount per 20,000 L (g)	Cost per g ($)	Source Supplier	Cost per 20,000 L ($)
Basal Medium	N/A	20,000	156 for 50L	Thermo Fisher	62,400
Ascorbic Acid 2-phosphate	64	1280	7.84	Cayman Chemicals	10,035.20
$NaHCO_3$	543	10,860	<0.01	Alibaba (averaged across multiple suppliers)	2.39
Sodium Selenite	0.014	0.28	0.1	Alibaba (averaged across multiple suppliers)	0.03
Insulin	19.4	388	340	Sigma	131,920
Transferrin	10.7	214	400	Sigma	85600
FGF-2	0.1	2	2,005,000	R&D Systems	4,010,000
TGF-β2	0.002	0.04	80,900,000	R&D Systems	3,236,000
Total Cost per 20,000L					**7,535,958**
Cost per litre					**376.8**

According to Table 3.4, the growth factors, FGF-2 and (TGF-β2) are the major contributors to the cost. Whilst this contradicts findings of Humbird who noted that these growth factors would not have a significant influence on the cost (particularly in large scale production), they are still worth discussing as they form a key part of Specht pricing model. Humbird's justification for this is that growth factors have been shown to only contributre about $3 to $4 per kg of wet cell mass at a 100 kTA scale. Therefore, production on an even larger scale would almost render growth factors insignificant to the cost.

Table 3.5: Summary of modelled scenarios for potential cost reduction purposes (adapted from Specht et al.,2020).

Scenario A	Reduce the concentration factors of all four growth facors (insulin, transferrin, FGF-2, and TGF-β) by 10-fold relative to the base case
Scenario B	Scale up the two most expense growth factors (FGF-2, and TGF-β) so that their cost is equal to that of transferring in the base case
Scenario C	Combination of scenarios A and B
Scenario D	Produce all four growth factors at $4 per gram
Scenario E	In addition to scenario D, obtain bulk, food-grade sourcing for basal medium components
Scenario F	In addition to scenario E, replace the ascorbic acid-2-phosphate with ascorbic acid
Scenario G	In addition to scenario F, replace HEPES (a component within the Basal Medium) with TES.

Table 3.5 presents scenarios outlined by Specht (2020) with the potential to reduce production costs. Some scenarios include single changes which can impact costs, whilst others include combinations of scenarios, for example, scenarios C and E. Scenario G presents the most alterations as a means of cost reductions. Figures relating to these scenarios are presented in table 3.6 and are examined further in the discussion section.

Table 3.6: Projected costs and fold reduction relative to the initial cost model presented in table 3.4 for a 20,000L batch of medium made under scenarios A-G.

Components	**Base Case**	**Scenario A**	**Scenario B**	**Scenario C**	**Scenario D**	**Scenario E**	**Scenario F**	**Scenario G**
Basal Medium	62,400	62,400	62,400	62,400	62,400	4,600	4,600	2,456
Ascorbic Acid 2-phosphate	10,035	10,035	10,035	10,035	10,035	10,035	4.48	4
$NaHCO_3$	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Sodium Selenite	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Insulin	131,920	13,192	131,920	13,192	1,552	1,552	1,552	1,552
Transferrin	85600	8,560	85,600	8560	856	856	856	856
FGF-2	4,010,000	401,000	800	80	8	8	8	8
TGF-β2	3,236,000	323,600	16	1.6	0.16	0	0	0.16
Total Cost per 20,000L	**7,535,958**	**818**	**290774**	**94271**	**74854**	**17054**	**7024**	**4879**
Cost per Litre	**376.80**	**40.94**	**14.54**	**4.71**	**3.74**	**0.85**	**0.35**	**0.24**

Evidently, as represented in table 3.6, scenario G provides the highest cost reduction to $0.24 from the base case presented ($376.80). This is followed by scenario F and scenario E, at a cost of $0.35 and $0.85 respectively. It is notable that in scenario A, where there was a 10-fold reduction in the costs of the growth factors, an overall cost reduction by almost 90%. Whilst figures presented relating scenario E, F and G appear promising, much work would be required to achieve such numbers. This point is further explored in the discussion section.

Specht (2020) further used these figures to project media costs per kg of meat, as outlined in table 3.7. Because cultured meat production has not yet occurred at an industrial scale yet, scholars cannot be sure exactly how much media will be required for cultured meat production. Specht's model considers high, medium and low media use. Obviously, lower media use will incur a lower production cost. Table 3.7 shows that the base case is ludicrously high and would not be economically viable. Scenario's A to G are perhaps more economically viable in the low media use category. Once again, Scenario E, F and G are the most appealing from a cost perspective. However, they are not without their technical challenges.

Table 3.7: Medium raw material cost contribution per kg of meat for batch production using high, average and low volumes of medium at various raw material costs (adapted from Specht et al., 2020).

	Base Case ($376.80/L)	**Scenario A** ($40.94/L)	**Scenario B** ($14.54/L)	**Scenario C** ($4.71/L)	**Scenario D** ($3.74/L)	**Scenario E** ($0.85/L)	**Scenario F** ($0.35/L)	**Scenario G** ($0.24/L)
High media use	$1,5072.00	$1,637.6	$581.60	$188.40	$149.60	$34.00	$14.00	$9.60
Average media use	$8,612.57	$935.77	$332.34	$107.66	$85.49	$19.43	$8.00	$5.49
Low media use	$2,153.14	$233.94	$83.09	$26.91	$21.37	$4.86	$2.00	$1.37

Risner et al (2020) highlighted that media costs for cultured meat in Specht's model would need to be reduced to the point presented in scenario G at $0.24/L from the base case at 376.80/L in order to be competitive with conventional meat. Risner et al (2020) further note that major there would need to be technological advancements on multiple fronts where media costs are reduced from 376.80 US$/L to 0.24 US$/L. Both Specht's (2020) and Humbird's (2020) modelling highlight expensive media costs at a base, however, they have offered some solutions as a means of reducing costs. Some solutions have been found to have more potential and be more realistic than others. This is further discussed in section 4.3.2.

3.2.3 Bioreactors

3.2.3.1 Bioreactor Equipment Costs

Of the studies researched and utilised in this report, all identified that a bioreactor is required for the scaling up and bulk production of cultured meat. Whilst there are some conflicting thoughts about the cost of bioreactors, some industry experts and researchers have estimated that the cost of a single 20 m^3 food-grade bioreactor is $750,000 to $1.5million (Risner et al., 2020; Humbird 2020). With installation costs and contractor’s fees included, this figure may be close to $2 million (Humbird, 2020). Table 3.8 provides a breakdown of the equipment parts as justification for the price noted (this includes installation prices) and totals $1.5 million which is evidently a significant cost contributor to cultured meat production.

Table 3.8: Cost breakdown of bioreactor equipment.

Part / Cost	**Price ($)**
Vessel & Agitator	330
Piping	360
Instrument/Electrical	476
Other direct costs	22
Additional internals/externals	164
Add for surface treatment	132
Total	**1.5**

*Prices are in American Dollars ($).

It is notable that in a study by Risner et al (2020) costs associated with bioreactors was the primary driver of capital costs in cultured meat production. Moreover, to displace the demand for beef in the U.S. by 1%, the scenarios ranged from requiring the deployment of 5205 to 50 bioreactors (20 m3) at a total capital cost of 4 billion to 37 million U.S. dollars (Risner et al., 2020).

3.2.3.2 Bioreactor Capacity

Studies have identified that a bioreactor size of $20m^3$ is the most suitable for cultured meat production at an industrial scale. However, a bioreactor of this size is not without its limitations. Figure 3.6 summarises findings of a study by Tramper and Van der Wheel (2014) which ultimately indicates that a bioreactor of this size is capable of producing 25,600kg per year. This study concluded that this would meet the demand of 2560 people (10kg per person, per year). Based on these assumptions, a bioreactor of 20 m3 can thus supply the meat demand (10 kg per person per year) of 2,560 people, a small village.

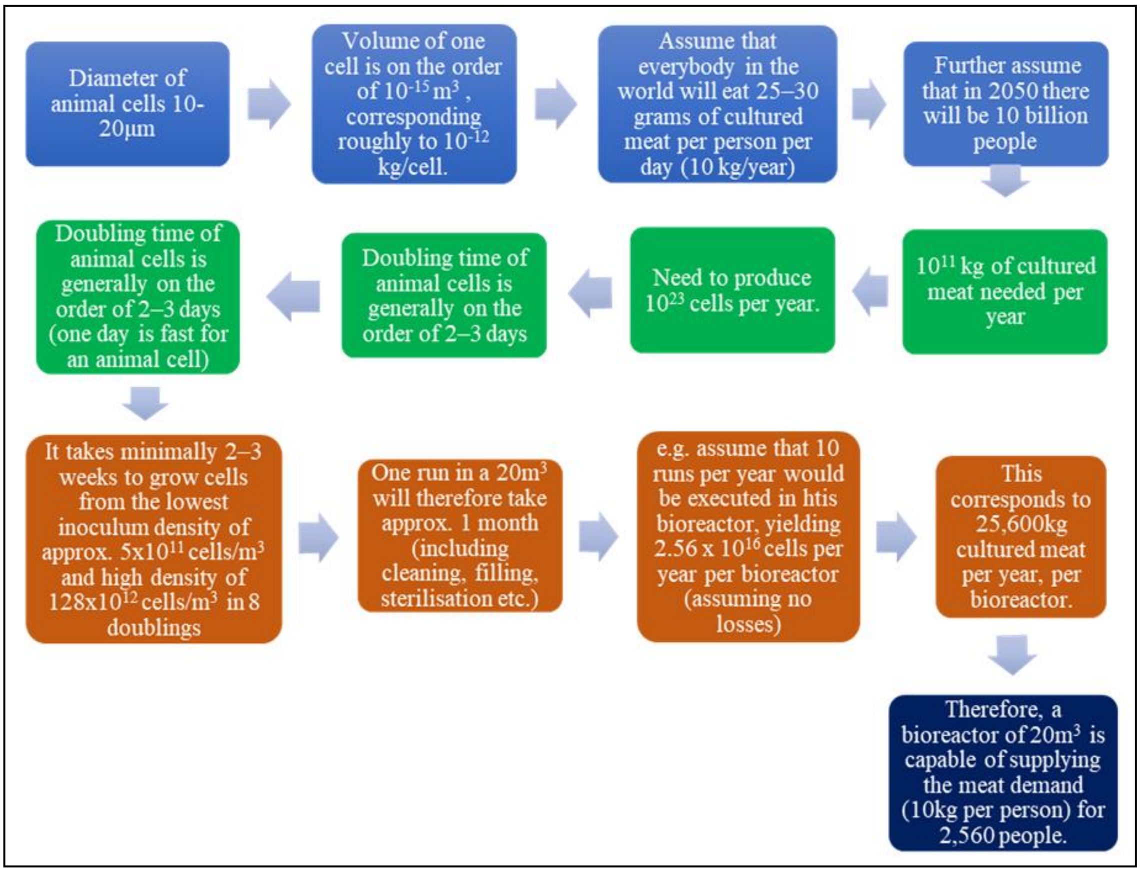

Figure 3.6: Case study outlining amount of meat capable of being produced using 1x20m^3 bioreactor.

To put this case study into perspective, Tramper and Van der Wheel (2014) estimate that the cost of minced meat in Europe is approx. €5 per kg, which would mean that a bioreactor which produces 25,600kg of meat per year would earn €128,000 per year (if sold at the going rate of conventional minced meat). By plugging these figures into the case study by Humbird (2020), an estimation can be made of how much product a cultured meat production facility can generate per year. Humbird identifies that 24 bioreactors in a facility is the optimum number. Using Tramper and Van der Wheels figures, which assumes that 1 bioreactor is capable of producing 25,600 kg, the following calculation can be conducted:

25,600kg x 24 = 614,400kg (approximately 614 metric tonnes)

According to the Agriculture and Horticulture Development Board (AHDB) (2020), in 2020 the UK produced approximately 926,000 tonnes of beef and veal. Based on

Tramper and Van der Wheel's (2014) model, over 1500 cultured meat facilities, comprised of 24 bioreactors each would be required to generate the same output for beef and veal alone. It is notable that, as of 2020, there were less than 200 red meat abattoirs operating in the UK, almost 8 times less than the amount of cultured meat facilities which would be required to produce the same output. Such statistics would imply that perhaps larger facilities with more bioreactors would be a better and more efficient way of generating the same output. It is notable that Humbird's study attempted to use a 48 and 96 bioreactor scenario but showed failure. Once the number of bioreactors went above 24, the production was not viable for various reasons. These reasons are analysed in the discussion section.

3.2.4 Timing

As previously mentioned, the proliferation rate of animal cells is slower than that of microbial cells (Shaikh et al., 2021). This further adds weight to the bioreactor limitations noted above as a greater bioreactor volume is required to achieve the desired number of animal cells. It has already been mentioned that bioreactors, which are larger than $20m^3$ are undesirable and so increasing volume has not been deemed an option for scaled up production of cultured meat. Therefore, to combat this, the production batch times are longer. Humbird (2020) made a comparison of animal cells with baker's yeast, which has a doubling time of approximately three and a half hours. It is notable that after one week of inoculum preparation, a batch of yeast would last around 16 hours. Assuming a doubling time of 24-48 hours, a factory producing an equivalent amount of animal cells would need between eight and sixteen more bioreactor volume (Humbird, 2020). As a result, production batches would last several days to a week, after subsequent months of inoculum preparation.

Doubling times and meat volumes will have a significant contribution to the capacity, cost and ultimately the viability of cultured meat. Specht (2020) attempted to estimate how long it would take to produce a given amount of meat. In order to do this, an inoculation density of 200,000 cells/ml was used as the cell source/starter cells. Furthermore, it was assumed that the maximum cell density at each proliferation stage was 4×10^7 cells/ml. The total cell volume was then calculated to be $4m^3$ or 4,000L, which was then doubled to account for void space for the flow of nutrient medium through the cells and scaffold. To expand a culture from $2x10^5$ cells/ml to $4x10^7$cells/ml, a 200-fold increase is required, which is the equivalent of seven and eight cell doublings. In order to estimate doubling times, Specht used figured from Accellta (a stem cell company), which indicates that in high-density cultures, a 50-to-100-fold increase could be expected in seven days. This equates to approximately 28 hours per doubling (so in this scenario, 6 doublings or a 64-fold increase would occur in seven days). In animal cell culturing, 24 hours per doubling is usually the standard (similar to the numbers noted above).

Considering this data which has been provided, it can be assumed that each stage of the cultured meat process will take approximately 9.3 days. For the purpose of this study, this has been rounded up to 10 days per stage. From a 2.5ml vial of frozen cells to one quadrillion mature cells, the result is a total residence time of 40 days. This figure is not optimal in terms of efficiency of the process. Therefore, Specht further outlines possibilities for cultured meat production in a semi-continuous process which has the potential to increase efficiency. Two scenarios were explored. For the purpose of these examples, the word 'harvest' refers to harvesting from the proliferation tank for seeding onto the scaffold in the maturation bioreactor (where cells mature for 10 days).

Scenario 1: 50% of cells are harvested. This means that when the 20,000L proliferation bioreactor reaches its harvest density, only 50% of the cells are harvested for seeding onto the scaffold for subsequent maturation. The remaining 50% of cells will be 'topped up' with fresh medium to replenish the volume to 20,000L. These cells are then left to proliferate for another 28 hours (equivalent of one doubling) until they reach the harvesting density again. This process is repeated and is summarised in table 3.9. At the final harvest, the entire volume is harvested (during which an there is an addition 10,000-20,000L of medium may be required).

Scenario 2: This involves the same process, however, 90% of the cells are harvested. 10% of the cells remain in the proliferation bioreactor and require a 10-fold increase (around 3.2 doublings). This subsequently requires approximately 3.7 days between harvests. In this scenario, between 18,000-36,000L of medium will be required for each additional harvest.

Both scenarios are summarised in table 3.9, which provides a comparison of both scenarios including their yield, doubling times and production runs. Evidently, the longer the production run, the greater the yield (kg). Significance of these findings are debated in the discussion section.

Table 3.9: Proliferation capacity requirements of the cell line, total meat yield for a multi-harvest production run, and overall length of the production run for several operational modes of semi-continuous production (Adapted from Specht, 2020).

50% harvesting scenario				**90% harvesting scenario**		
No. of harvests per production run	Total meat yield per production run (kg)	Required proliferation capacity (doublings)	Approximate length of the production run (days)	Total meat yield per production run (kg)	Required proliferation capacity (doublings)	Approximate total length of the production run (days)
1 (batch)	3,500	24	40	3,500	24	40
2	5,250	25	41	6,650	27.2	44
3	7,000	26	42	9,800	30.4	47
4	8,750	27	44	12,950	33.6	51
5	10,500	28	45	16,100	36.8	55
6	12,250	29	46	19,250	40	59
7	14,000	30	47	22,400	43.2	62
8	15,750	31	48	25,550	46.4	66
9	17,500	32	50	28,700	49.6	70
10	19,250	33	51	31,850	52.8	74

3.4.5 Building Costs

Using Humbird's (2020) study, building costs may be as high at $48.5 million for the feed batch process. This comprises a facility which includes a cell culture area, cell lab, quality control (QC) lab, offices, compressors, a shop and warehousing. At a cost of almost $40 million for the cell culture area, this contributes around 80% of the building cost. The building costs for a facility carrying out the perfusion process is significantly higher, at a cost of approximately $65.5 million (Humbird, 2020). The cell culture area similarly to the feed batch process incurred the majority of the cost ($49 million). Regardless, whether $49 million or $65.5 million, clearly colossal start up investment would be required which may not be feasible for many private companies without private investors or financial aid from governments.

3.4.6 Operating Costs

Operating costs are another key contributor to the overall cost of cultured meat production. Whilst media costs are incorporated into the operating costs, there are still other elements which contribute significantly to the overall operating costs. Labour is one element which should be considered in relation to operational costs. Humbird's model, provides a cost of $13,730,000 per year using the perfusion process and $9,900,000 using the feed batch process. This somewhat conflicts with Risner's (2020) model which highlights a labour cost of approximately $15 million per year in the best-case scenario and $1.5 billion per year in the worst-case scenario. Moreover, utilities should also be taken into consideration. It is notable that utility costs will vary based on location and depending on which type of production process being used. A comparison of these figures is provided in section 3.4.7.

Additionally, consideration should be given to the need to an aseptic production facility. The neutral pH and a temperature of approximately 37 ◦C within the bioreactor is an ideal breeding ground for microbes (Humbird, 2020). Therefore, introduction of an undesirable microbe with the potential to cause harm could result in total batch contamination and a result, a batch loss. Thus, it is highly important that the equipment, environment and the media are clean and free from microbial contamination at all stages of the cultured meat production process.

Some precautions which may be taken in this case are extra steam piping for point sterilisation, additional automation to prevent contamination by operators and containment considerations for biosafety (Risner et al., 2020). These measures can help reduce contamination risks, however they are not without their additional expense and so, aseptic production costs need to be incorporated into the operational costs. Whilst some have made the comparison between the cultured meat process and a brewery, once an aseptic operation is factored in, the building for the cultured meat processing will incur a cost that is more than double the cost of a brewery building (Humbird, 2020).

3.4.7 Summary of Total Costs

So far, results have outlined individual costs for process components. This section aims to draw a summary of these costs together, to give a final production cost. Measurements of the two types of production systems; feed-batch process and perfusion process have been included and are summarised in table 3.10. As can be seen from table 3.10, in relation to variables, macronutrients are the highest contributor to the cost, followed by micronutrients in both processes. These figures are consistent with scenario D and E of Specht's (2020) model for the media which indicate a macro and micronutrient cost totaling approximately $21/kg (at low media use) and around $19/kg (medium media use) respectively. Moreover, in terms of fixed costs, annual insurance fees also incur a significant cost.

Overall, the operating costs of the perfusion process are almost 20% higher than the feed-batch process, according to Humbird (2020). Whilst labour costs are the lowest of the variables, it is notable that they contribute between $1.45 and $1.99 to the final cost per kg. Moreover, among utilities in the feed batch process, water is estimated to cost $0.57/kg meat, followed by power/electric costs which equate to $0.35/kg meat (Humbird, 2020). Within the perfusion process incurs similar utility costs, with water and power costing $0.53/kg and $0.44/kg meat respectively (Humbird, 2020).

Table 3.10: Total cost of production per batch, per year and per kg using the feed batch and perfusion batch processes (Adapted from Humbird, 2020).

	Feed-batch process			**Perfusion process**	
	$/batch	$/year	$/kg	$/year	$/kg
Macronutrients	35,300	130,130,000	19.08	127,044,000	18.39
Micronutrients	5,600	21,364,000	3.13	19,225,000	2.78
Consumables	1,600	5,825,000	0.85	31,503,000	4.56
Utilities	1,700	6,437,000	0.94	6,747,000	0.98
Total (variables)	44,400	163,755,000	24.01	184,518,000	26.70
Burdened labour cost	2,700	9,900,000	1.45	13,730,000	1.99
Annual maintenance	3,600	13,116,000	1.92	26,505,000	3.84
Annual insurance	4,400	16,395,000	2.40	33,131,000	4.79
Total (fixed)	10,700	39,412,000	5.78	73,366,000	10.62
Annual Capital Charge	13,000	47,771,000	7.00	96,536,000	13.97
Total Cost of Production	**68,000**	**250,938,000**	**36.79**	**354,420,000**	**51.29**

3.4.8 Retail Cost Considerations

Projected retail costs of cultured meat have varied among researchers. Humbird's (2020) model presents a bulk cell-culture processing facility which include twenty-four 20 m^3 fed-batch bioreactors which estimated a production of 6.8 kTA of wet cell mass with a production cost of $37/kg. The largest contributor to the cost in this model was the amino acids ($19/kg), followed by capital and facility overhead. Humbird further anticipated a potential production cost of further processed products (e.g. burgers, nuggets and meatballs) of $25/kg. However, such a product would be expected to retail at a minimum of $50/kg at a supermarket once the retailer's markup is added (Humbird, 2020). Risner et al (2020), provided a case study which presented four scenarios. The cost of production per kg in Risner's (2020) scenario 1 was approximately $400,000. Scenario 2 and 3 present lower projections of $57,000/kg and $44,000/kg respectively. The major driver for these projections were the cost of the bioreactors. Scenario 4 returns a cost of $2/kg, accompanied by a reduction in the number of bioreactors in the facility. Scenario 4 is the only scenario that returns a potential cost which is lower than the conventional cuts highlighted in table 3.11.

A case study carried out by Specht (2020) attempted to project costs of medium per kg meat. Whilst this does not calculate total cost of production per kg, for the purpose of the research, medium costs were combined with Humbird's (2020) operating and building costs to make a prediction of price. Humbird's feed batch process costs were selected as they were cheaper and totalled $36.79. Specht's media costs ranged from $15,072/kg to $1.37/kg. Therefore, it can be summarised that a 'worst case scenario' cost using this method would be $15,108/kg and in the best case, costs would be just over $38/kg. Even if retail markup was a small margin of 20%, this would still entail a retail cost of $45.60 in the best-case scenario, still higher than every cut of conventional meat presented in table 3.11. Furthermore, a study by Van der Wheele and Tramper (2014) established a projected media cost per kg of cultured meat to be approximately €8 ($9). Using the same method, applying Humbird's operational costs to this price returns a production cost of approximately $46/kg.

Table 3.11: Table showing prices per kilogram of different cuts of beef, pork and chicken* (Adapted from the U.S FAO (2021)

Species	**Cut**	**$/kg**
Beef	Ground Beef	10.38
	Extra lean ground beef	14.02
	Sirloin Steak	25.64
Pork	Bacon sliced	16.08
	Pork Chops	9.66
	Ham (pork)	10.92
Chicken	Chicken (boneless breast)	7.90
	Chicken (leg, bone-in)	3.76
	Chicken whole	3.31

*Figures are representative of prices in the United States of America and are in American Dollars.

3.4.9 Meat Tax

To the knowledge of the author, at the time of writing, there are currently no additional taxes on meat (other than standard Value Added Tax (VAT) applied to all food products) anywhere in the world. Literature searches concurred with this and did not show evidence of any current additional meat taxes. However, some studies did explore the possibility of a higher meat tax introduction and the effect this could have on the retail cost of meat for the consumer. It is noteworthy that studies who modelled meat taxation, generated projected tax increases based on the emissions of individual commodities. Therefore, different taxes were applied to different species of meat, such as beef, pork and chicken.

A study by Säll and Gren (2015) was conducted in Sweden and taxation was based on Carbon Dioxide (Co2), nitrogen, ammonia and phosphorus emissions. This study focused on beef, pork, chicken and some dairy products. For the purpose of this research, the dairy results will not be discussed, although it is worth mentioning that the three meats used in the study were all higher than the dairy products. The study found that beef was the worst offender, followed by pork and chicken respectively. The calculated tax increase for such products was as high as 50% as a result. Similarly, a study carried out in the Netherlands by Broeks et al (2020) anticipated a 15-30% tax increase on meat products. It is notable however, that this study also included negative human health effects associated with meat consumption as part of the calculation.

3.4.10 Cultured Meat vs Conventional Meat Comparison

To conclude the results section, a comparison of aspects of conventional and cultured meat is carried out and is summarised in Table 3.12. In terms of land use, a study carried out by researchers in Maastricht University in the Netherlands, found that a single cow can be the donor of enough cells to produce almost 44 million pounds (20 million kilograms) of beef (Iyer and Iyer, 2020). Comparative to this, a livestock production system would need approximately 440,000 cattle to generate the same output (Ewing-Chow, 2019). When consideration is further given to the amount of land, water, feed required for this livestock production, it seems that cultured meat is the more favourable option. However, it should not be overlooked that cultured meat too, has its own negative contribution to GHG emissions and overall impact on the environment.

Table 3.12: Comparison of different aspects of cultured meat and conventional meat (adapted from Hong et al., 2021).

Attributes	**Conventional Meat**	**Cultured Meat**
Production System		
Production Method	Animal Farming	Cell Cultivation
Land Requirement	High	Low
Location of production facility	Most Rural	Rural and Urban
Production cost	Relatively high	Very high
Production Time (including rearing)	Long	Medium-long
Production yield	Low-medium	High
Greenhouse Gas Emissions	High	Low
Energy Requirement	High	Low-medium
Water and Soil pollution	High	Low
Sustainability	Low	Relatively high
Characteristics		
Manipulating composition	Impossible	Possible
Food Safety	Low-medium	High (when produced aseptically)
Animal Welfare	Low	High
Ethical Advantage	Low	High
Consumer Acceptance	High	Low

In comparison with conventional meat, some scholars have stipulated that cultured meat could require up to 99% less land and 45% less energy for its production (Iyer and Iyer, 2020). It was further noted that cultured meat may produce up to 96% less greenhouse gas emissions (Iyer and Iyer, 2020). The original perception of cultured meat as such a promising development in relation to the environment is based on modelling by (Tuomisto and Teixeira de Mattos, 2011). However, these claims have been subject to much scrutiny and will be explored further in the discussion section. It is notable that the study found that with poultry production, culturing methods could require 37% more energy than that of conventional production. Cultured meat has evidently been perceived as a more sustainable protein alternative than it's latter, conventional meat. This perception is analysed further in the results section. It is also notable, as depicted in table 3.12, that whilst there may be differences in organoleptic properties of the two, cultured meat has the potential to be manipulated.

As shown in section 3.2.4 the production times of cultured meat can range between 24 and 51 days (Humbird, 2020; Specht, 2020). The processing time of conventional meat is between 1 and 5 days but be more depending on aging requirements. Whilst it is difficult to make a comparison due to the differences in processing, livestock rearing times should be considered in relation to times. This is analysed further in the discussion section. Moreover, factors such as costs and yields have already been highlighted earlier in the results and will be discussed further in section 4.

Chapter 4: Discussion

4.1 Chapter Introduction

The relative price of conventional meat currently presents extra difficulty when it comes to brining cultured meat to the market. Whilst cultured meat can perhaps offer a potentially more sustainable, environmentally friendly alternative to conventional meat, it is difficult to perceive it being successful without achieving a competitive price. Hence, this provides substance for need to reduce the cost of cultured meat production. This chapter will analyse the results presented in section 3 and provide explanations for some of the figures obtained.

4.2 State of the Industry

The results section indicates that there has been much progress made in the cultured meat industry with a large number of companies now well established in the industry. The number of companies indicates that even at this early stage, the market will be a competitive one. It could perhaps be considered a 'race' among companies to produce an economically viable cultured meat product which could help gain competitive advantage. CE Delft (2021) highlight that the maturity of business processes in this industry is quickly increasing and that in terms of a timeline, companies are aiming for industrial scale production and competitive prices in the 2030's. It is notable that this is still a long way off and that much work is needed in the way of producing cultured meat at a lower cost. This is discussed further in the next section. Moreover, findings that over 45% of companies identified in this research were founded less than 2 years ago compliments the findings from CE Delft, indicating a quickly maturing market with an increasing number of stakeholders who are trying to establish themselves in the industry.

Some of the investment figures further add weight to the idea that the cultured meat industry is developing at a fast rate with over $460 million invested between 2016 and 2020. Moreover, at presented in table 3.1, the products highlighted are all further processed meat products and there were no 'whole cuts' mentioned, for example, a chicken nugget was developed by Peace of Meat and a meatball was produced by Memphis Meats. Whilst progress has been made in the production of cultured whole cuts, such developments are at their early stages (Kang et al., 2016). The general consensus is that companies are focusing on further processed cultured products at this time due the better feasibility of replicating sensory characteristics of conventional counterparts. Section 1.1.4.3 provided an insight to suitability of cultured meat towards further processed products.

4.3 Techno-Economical Considerations

4.3.1 Cell Source

Meat from industrial animals, including cattle, pigs, poultry, and fish, consists mainly of skeletal muscles, fibroblasts, and adipose cells (Hong et al., 2021). It is noteworthy that skeletal muscles have the ability to regenerate and self-renew due to the presence of stem cells (Laumonier and Menetrey, 2016). As previously mentioned, characteristics of animals can impact both the yield and quality of the culturing cells (Shaikh et al., 2021). Age of the donor animal is a key parameter that, if optimised can positively impact culturing. Notes that stem cell content of muscle decreased considerably with age and that a rapid decrease of stem cells occurs during the first months after birth (Melzener et al., 2020). Therefore, the earlier in life that stem cells can be obtained, the greater the efficiency of the culturing process. Furthermore, since satellite cells from younger animals have undergone less mitotic cell divisions, it can be presumed that they will retain their differentiation capacity for a longer proliferation period (Narbonne, 2018).

Animal gender has also been shown to have an impact on yield and quality of stem cells (Melzener et al., 2020), as well as different cattle breeds. Coles et al. (2015) found that there were differences in the proliferation rate of satellite cells from Angus, Hereford, and Wagyu cattle. It is also notable that the cut from which the donor sample may have different composition. For example, the chuck muscle in cattle contain primarily Type I fibers, while the fibres of the round mainly contain Type II (Stephens et al., 2018). Moreover, animal husbandry conditions have the potential to impact fibre composition, as more intensive husbandry conditions (Coles et al., 2015). It is also notable that there may be variations relating to the factors noted among different species of animals (Shaikh et al., 2021). To optimise the cultured meat production process, it is imperative that more research and development is conduction in this area to establish the best age, breed, muscle cut and other factors which will influence yield and quality of animal cells. This will ultimately contribute economically to cultured meat production.

As alluded in the results section, there is much debate surrounding the best source of the starter cells. Tissue engineered animal cells and spontaneous mutations have the ability to reduce dependency on fresh tissue samples (Stephens et al., 2018), which would favour the argument for better animal welfare associated with cultured meat and eliminate the risk of error during extraction. This type of cell line also has the potential to increase the proliferation speed and differentiation (Melzener et al., 2020). Whilst this may seem favourable, it is notable that cell lines cannot continue forever. Most cells have a limited division capacity, which is often referred to as the Hayflick limit (Zhang et al., 2020). This provides some explanation of result relating to ‘timing’ as to why cell lines cannot proliferate indefinitely. The Hayflick limit is determined by the telomere length at the end of a chromosome, which shorten after each replication (Zhang et al., 2020). It has been suggested that the addition of telomerase (an enzyme which repairs the telomeres of the chromosomes) could be used to facilitate scale up and rapid production of cultured meat (Munteanu et al., 2021). Much work is still required in this area to incorporate the use of telomerase into the production process.

Moreover, tissue engineering methods are subject to undesirable complications, as there is a potential for sub-culturing, misidentification and continuous evolution (Shaikh et al., 2021). Additionally, often these cells are not representative of the primary cell and for example, can demonstrate different growth rates (Stephens et al., 2018) and so one should be dubious about these types of cell lines. Traditionally, the more common and preferred cell source is cells obtained from the animal or herd of animals.

4.3.2 Media

Findings in relation to media costs form a highly significant part of this research. It is evident that if media costs cannot be lowered, then cultured meat will not be viable for commercialisation due to the high final cost incurred to the consumer as a result. Even though results presented the lowest media cost contribution to be 55%, this is still too high for feasibility. Therefore, it is imperative that such costs are reduced to an absolute minimum in order to make the scaling up of cultured meat economically viable (Leong et al., 2017; Warner, 2019).

As briefly mentioned, FBS has been a commonly used component in culturing media in previous decades. However, its use is controversial for various reasons. Ethically, FBS has caused concerns as its collection causes unnecessary suffering for the unborn calf (van der Valk et al., 2004). Additionally, there may be seasonal and continental differences in the serum composition, which can result in batch variations (van der Valk et al., 2018). Further concerns are highlighted in relation to contamination of FBS, for example, with Bovine Spongiform Encephalopathy (BSE) rendering it unsafe for the consumer (Schiff 2005). Some scholars claim that 20-50% of commercial FBS contains a virus (van der Valk et al., 2018). Finally, it should be considered that there would also be ethical concerns among consumers in relation to consuming a product produced with such a controversial ingredient (Hawkes, 2015). Nonetheless, FBS is not a cost-effective solution to current cultured meat media on the market and so is not considered for use in any of the recent studies analysed.

It is important to note that while a generic formulation has been outlined in the results section, media composition will vary depending on the cell line (e.g. per species) and the production process. The main aim of the media formulation is to achieve the highest rates of cell growth and so this highlights the importance of the growth factors, which are highlighted in tables 3.3 and 3.4. Furthermore, the results section indicates that some components are much more expensive than others. Some scholars, such as Specht (2020) have attempted to model prices with formulation changes in order to bring costs down. Whilst these models prove very promising, one should be dubious, as these figures are perhaps idealistic, with much work and development required to achieve such numbers. As outlined in the results section, Humbird (2020) found that amino acid quantity in media formulation was the main cost contributor overall. Furthermore, there was a correlation showing that decreased availability of amino acids resulted in an increased cost which further adds weight to the cost problem. However, if cultured meat production did become prominent, then perhaps there would be a domino effect of upscaling production of such amino acids, thus reducing cost.

Additionally, the results section expresses plant hydrolysate (for example, soy) as a potential alternative to some amino acids. One initial positive is that plant hydrolysates are already produced on huge scales, not to mention being much more cost effective than regular amino acids as evident from table 3.3. Whilst they are only used in the media at quite low levels, they have still caused difficulty in that the hydrolysate preparation process can have a damaging effect on cell growth (Hartshorn et al., 2010). Such preparations involve the ultrafiltration of the hydrolysate to remove all protein (including the hydrolysing enzyme) and peptides, pasteurised, and spray-dried for storage (Humbird, 2020). The nature of these processes results in the production process being fairly expensive. A further disadvantage of using an alternative such Soybean hydrolysate is that it does not contain the essential amino acids (EAA's) L-glutamine and L-tyrosine. Therefore, these components would have to be further added to the media.

Furthermore, the results section highlights environmental issues associated with soy hydrolysate, including high land use, deforestation and loss of biodiversity (Gil, 2020; WWF, 2014). While conventional meat has been subject to much scrutiny for its negative impact on the environment, it seems that many studies have failed to highlight the latter negative impacts of cultured meat on the environment. Soy hydrolysate is just one example of how cultured meat can be damaging to the environment. Since studies have been futile in addressing these issues, comparative data is unavailable to determine which of the two (conventional vs cultured meat) has a worse impact on the environment and is more sustainable.

Another possible way that media use can be made more efficient and cost-effective is through recycling of some components which will ultimately reduce waste and reduce the amount required. The pH bffers (HEPES) are capable of achieving this if an efficient separation or filtration system is introduced. If successful, this could help reduce the cost of the basal medium by 38% (Specht, 2020). Furthermore, it is significant that price projections of media components are based on that of the pharmaceutical industry and are packed at very high purity to ensure sterility (Humbird, 2020). Food grade materials may not incur such a cost since only an aseptic product is required. Since media components are not currently produced at a high scale for food use, it is difficult to project how much cost would be reduced once the sterility factor has been removed.

In addition, scholars still cannot agree on the exact amount of media which will be required for cultured meat production (CE Delft, 2021; Humbird 2020; Specht, 2020) and so low, medium and high usage scenarios have had to be projected. The high usage media costs established in the results section are not economically viable for cultured meat production. Therefore, researchers must work towards establishing a process which requires minimum media usage.

4.3.3 Bioreactors

The results section indicates that most studies agree that a 20m^3 bioreactor is optimum for cultured meat production. This is due to the animal cells being sensitive to higher hydrostatic pressures in comparison with fungal or bacterial cells which can be viable in >500 m^3 scale bioreactors (Habegger et al, 2018). It was initially thought and hoped that larger (≥200 m^3) stainless-steel tanks with a greater production capacity would be used for cultured meat, perhaps resembling that of a large-scale fermentation plant or a brewery (Spitter, 2021). This would have been more efficient and capable of producing larger quantities of meat had such issues not been encountered. While the culturing of cells process does resemble that of a fermentation process, animal cells present different technical and economic barriers. Additionally, cultured meat is limited by the animal cell’s ability withstand spatial heterogeneities, such as, fluctuations in temperature, pH, or nutrient concentrations (Humbird, 2020).

It is notable that animal cells proliferate more slowly than microbial cells adding an increased time requirement to the culturing process (Melzener et al., 2020). Moreover, it is also inconvenient that metabolically unregulated cells, such as those of animal cells can exhibit inefficiencies during culturing causing them to create unwanted, growth-inhibiting catabolites such as, lactate and ammonia (Humbird, 2020). As a consequence, there may be limitations in relation to mass-transfer, where gas sparging and agitation are limited by the potential for shear-induced damage to animal cells, which lack a rigid cell wall (Melzener et al., 2020).

On a final note, it is important to reiterate that bioreactor costs, presented in the results section are based on estimates for standard food-grade bioreactors and that more sophisticated bioreactors (more suitable for cultured meat) may increase capital costs considerably. Another shortcoming of the studies presented in the results section are that they did not place much emphasis on waste or batch losses. Whilst in vitro meat production is a highly sophisticated process, it is inevitable that there may be complications which can result in waste or loss of a batch. Perhaps the most obvious outcome from section 3.2.3 is the huge capital costs of the bioreactors which would require very high start up investments. Humbird (2020) suggested that 24 bioreactors in a factory or cultured meat facility is optimal. Given the costs outlined by Humbird (2020) of approximately $1.5 million per bioreactor, a facility of 24 bioreactors would incur a cost of 36 million on bioreactor equipment alone. One may be dubious to invest so much into large scale production without knowing for sure the viability of the entire process as such a scale.

4.3.4 Timing

While densities as low as 100,000 cells/ml have been presented and may be viable for some cell types, studies have conservatively lowered this to account for variables (Risner et al., 2020). This number can potentially be pushed even lower, which is promising, through selection of more sophisticated genetic techniques which allow cells to tolerate low densities without triggering apoptosis (Specht, 2020). The results section of this research noted that the maximum achievable cell density was 4×10^7 cells/ml at the proliferation stage. Yet, some scholars have noted animal cell densities above 1×10^8. While this could be promising, as the number of cells produced in the process could be doubled or else reduce the volume of the tank required for the proliferation phase by 50%. However, this would require careful analysis and further trialling, as it can become difficult to prevent spontaneous differentiation among cells and to ensure uniform nutrient access and aeration (Choi et al., 2020).

As highlighted in the results, each stage has been found to take approximately 9.3 days. Specht opted to round this up to 10 days to be cautious and allow for any unforeseen processing issues which may arise. The total residence time indicated in the results section is presented as the possible longest time. This is due to overestimating and using 'worst case scenarios' to air on the side of caution. Whilst other companies have published estimates in the range of between two and four weeks, for example, Tramper and Van der Wheel (2014). It should be acknowledged that many factors were not considered in this model, such as cellular losses due to differentiation, cell death and other losses during cell harvesting or transfer. However, it is fair to say that the cautiousness of figures provided by Specht provide some sort of leeway if such factors were to be problematic in the process. Therefore, this model can be awarded with a reasonable degree of accuracy.

It is notable also that both of Specht's (2020) timing models present a semi-continuous process and so, consideration should be given to the number of bioreactors which would be required. There would be much additional capital required for this process, particularly in the models with more doublings as presented in table 3.9. Additional complexities should also be considered as a good process flow and efficient layout of equipment would be required to optimise production. Additionally, table 3.9 gives an indication of which approaches may be best suited for cultured meat production. For example, in the 50% harvesting scenario, at 33 doublings, slightly more meat is yielded. However, this would also involve 10 harvests in contrast to the 9-% harvesting scenario at the same number of doublings. Therefore, the 90% harvesting scenario in this case seems more favourable and may be more efficient. Specht (2020) also notes preferability of the 90% harvesting scenario as there is a reduced risk of loss of crashed cultures from contamination introduced during harvesting. To conclude the timings section, the key take out is that the most cost-effective scenario is one which yields the most amount of meat in the least amount time, without any batch losses or mutations.

4.3.5 Capacities

Studies presented in this research have outlined the amount of cultured meat a $20m^3$ bioreactor can produce over the course of a year. These projections are based on continuous and calculated runs at the same rate throughout the year. However, one major shortcoming, which studies have failed to identify is fluctuations in demand and volatility of some commodities within the food industry. It should be remembered that meat is a perishable food which does not have a long shelf life and so there is minimal room for error in forecasting production. For instance, there is generally an increased demand for meat over the Christmas season. The findings presented by scholars do not consider seasonality and are perhaps unrealistic as they assume a continuous and consistent flow of goods from input to sale to the customer. The long production times, as high as 48 days (Specht, 2020), further add to this issue in that it is more difficult to forecast.

On the other hand, of the most significant progressions in the industry, products such as burgers and nuggets have been produced and deemed organoleptically sound for consumers and so it is notable that such products have the potential to be frozen and sold as frozen. This would provide more leeway in terms of dealing with fluctuations in demand. Furthermore, Van der Weele and Tramper's (2014) findings are significant in outlining how many people one bioreactor can potentially feed. One bioreactor was found to be able to feed 2560 people who consume 10kg of meat on average per year. Considering the figures outlined in the introduction where the FAO (2009) highlighted that demand for meat is expected to double by 2050, it would take a huge amount of bioreactors to even meet a small fraction of this demand. Therefore, capacity constraints outlined in this research indicate that cultured meat, even once largely scales up, will unlikely ever be capable of eradicating conventional meat consumption.

4.3.5 Operating Costs

As briefly stated in the results section, labour can account for \$1.45 to \$1.99 per kg/meat. In perspective, it is one of the smallest contributors to the final cost noted, however, one may have assumed that given that cultured meat production is quite automated with highly sophisticated equipment and machinery, that labour costs would be lower. Perhaps this is a further area which requires additional work to bring costs downwards. It is notable that location of the cultured meat facility can impact the labour costs. For example, labour can potentially be reduced by approximately 25% if the facility was situated in Raleigh or Austin in the USA where minimum wage is lower (Humbird, 2020). Therefore, companies may be tactical in their site location to reduce expenditure. However, consideration should also be given to end customer and consumer as the further the distance from the customer the increasingly high the distribution costs.

Moreover, utilities have been shown to contribute almost $1 to the cost per kg of meat, with water costs contributing over half of this. This suggests that more research and development is required to reduce utilities, such as, the amount of water required for cultured meat production. However, this may be difficult considering the importance of effective cleaning in such a facility and so, current water requirements are likely justified for this reason. Again, geographical location of cultured meat facilities should be considered for reducing utility costs as some areas have lower utility charges than others. Finally, in relation to the cleaning point mentioned, aseptic production was noted as a requirement for a cultured meat facility. Failure to follow good sanitisation and cleaning procedures may result in batch losses through microbial contamination, deteriorated quality of product and ultimately loss of batches.

4.3.6 Retail cost considerations

This research has presented multiple factors which will ultimately contribute to the final retail cost of cultured meat. It is of the upmost importance that cultured meat be available at a price that is affordable to the consumer and competitive with that of conventional meat. Humbird (2020) made the point that in the past, it has been attempted to general new fossil fuels by bioengineering. The key motivator for this was the ever-rising price of fossil fuels and their limited availability. Such motivators are not the same for cultured meat, due to the relatively stable price of conventional meat (U.S Department of Agriculture, 2019), outlining less of an economic opportunity for cultured meat. This is further weighted by prices of cuts presented in table 3.11.

Evidently, there is difficulty being experienced in bringing cultured meat to a competitive price with that of conventional meat. However, one opportunity which perhaps favours the cost of cultured meat, would be the production of exotic meats which are usually expensive. For example, a batch production process at this scale would likely be feasible for something like sushi-grade tuna (which retails for upwards of $70 per kg), Japanese beef Wagu or perhaps even delicacies like caviar. It should be noted however, that the benefits of this would be purely economic and not contribute to the facilitators of cultured meat production highlighted in the introduction section.

In order for cultured meat to become competitive in the meat market, to assert affordability, some have suggested a target of approximately $25/kg of wet animal cell matter (Humbird 2020). Furthermore, some scholars have expressed concern that cultured meat has the potential to exacerbate inequalities between the rich and the poor (Bonny et al., 2015; Cole and Morgan, 2013; Stephens et al., 2018). Bonny et al., went as far as saying that cultured meat may be used to feed the masses cheaply, whilst leaving the ‘real’ meat to the wealthy population. On the contrary, Bryant (2020) suggests that with cultured meat being more expensive, this could allow the wealthy to eat meat without the moral consequences, while the poor would have to kill animals for their food.

Most of the prices noted in section 3.4.5 are much too high to be economically viable. These prices indicate that much work is needed to bring costs down to the best-case scenario models presented by those such as, Specht (2021) and Humbird (2020). Scenario 4 presented by Specht would be deemed to have potential in the marketplace. Risner’s (2020) model, if achievable would also be a more economically viable option. Based on the prices of conventional cuts presented in table 3.11, the $46/kg production cost highlighted in the results section would be the only ones with the capability of competing. However, it should be noted that prices modelled by Humbird (2020), Specht (2021) and Risner et al (2020), are vague in that they are not species specific. One would assume that there are some process deviations depending on the species in question which are not considered in these studies and prices. Therefore, variation would be expected in relation to the cost depending on the type of meat being produced. This could result in higher costs which have not been considered in these studies.

4.3.7 Meat Tax

The results section has outlined potential tax increases for meat products. Whilst the results disclosed tax increases consistent with negative environmental impacts, it is also worth mentioning that some taxes incurred a consideration of the negative health effects of meat. However, it is more likely that any future tax increases will be linked to the environment rather than human health. In relation to this concern, cultured meat seems a favourable alternative which, based on the models presented by those such as Säll and Gren (2015) and Broeks et al (2020), would be subject to 'avoidance' of such taxes. This would certainly entice a consumer to perhaps purchase cultured meat over conventional meat, once there is a substantial cost difference involved. This is of course, provided that there is sufficient evidence that cultured meat does not incur similar levels of damage to the environment or health to conventional meat.

4.3.8 Cultured Meat vs Conventional Meat Comparison

One of the major comparisons presented in literature relate to the higher environmental impacts of conventional meat as opposed to cultured meat. As mentioned in the results section, findings by Tuomisto and Teixeira de Mattos (2011) which have been vastly cited in further studies, have been subject to some debate. It could be said that some of the information in this article is 'cherry picked' in favour of cultured meat, whilst perhaps somewhat overlooking the negative findings. Iyer and Iyer (2020) suggest that these findings were delivered in the most optimistic light possible. Whilst the study did have some promising findings in terms of greenhouse gas emissions, it was not without its limitations.

Calculations of Tuomisto and Teixeira de Mattos (2011) were based on a mature and streamlined process, requiring few inputs and without cleaning of the bioreactor (which as shown by Iyer and Iyer (2020) entails costs and contributes heavily to water usage). Whilst this is not impossible, such assumptions may be deemed very optimistic and will require more sophisticated developments in the cultured meat industry. It is notable that while cultured meat production systems do require less land than traditional livestock systems, cultured meat requires four times more energy than traditional livestock (Alexander et al., 2017).

Evidently, as shown throughout this research, production costs of cultured meat are currently much higher than that of conventional meat and subsequently, retail costs of cultured meat a projected to be much higher than conventional meat cuts (as highlighted in section 3.4.8). Moreover, animal rearing times have been considered in relation to production time. Whilst the processing of conventional meat is relatively quick, animal rearing can be several years, which contributes to GHG emissions, land use and animal feed requirements, all of which negatively impact the environment. Moreover, the results allude to the potential manipulation of cultured meat. This was briefly discussed in the introduction section and could have benefits for the consumer. For example, manipulation of beef could be carried out to reduce fat content. This has the potential to give cultured meat a competitive advantage in the market.

4.3.9 Other Considerations

There were other factors which were not referenced in literature which have the potential to add to the costs of cultured meat production. It is still unknown what regulatory requirements will be associated with cultured meat production. Hence it is difficult to check the level of quality control (QC) checks and batch testing which will be required. It should be considered that increased QC and batch testing will result in an increased cost. However, considering cultured meat production is a more automated process than conventional meat production, there is a high possibility that QC checks and batch testing associated with cultured meat may be lower. As mentioned, studies analysed as part of this research have not factored these costs into their models.

Furthermore, the literature reviewed as part of this research did not specifically refer to the chilling and storage of cultured meat, nor the final shelf-life of the cultured meat products being produced. Moreover, some, such as Bryant and Sanctorum (2021) express concern relating to the impact that cultured meat may have on livestock farmers. Attempts to restrict cultured meat have been conducted as it has to potential to replace livestock farming which would clearly cause concern among meat farmers (Bhat et al., 2015). Whilst in the EU, agricultural employment is approximately 4.4% of employment, this percentage is higher in less developed countries (Roser, 2019). Therefore, economical viability of cultured meat should not only consider the costs of its production, but also the economic impact it can have from a livelihood and employment perspective. Moreover, many agricultural workers live in rural areas where the economy is largely dependent on agriculture (Bryant and Sanctorum, 2021). Scale up of cultured meat could severely impact the agriculture industry and result in agricultural job losses.

Chapter 5: Limitations, Future Work and Recommendations

5.1 Limitations

While this study presented a thorough analysis of the economic viability of cultured meat in relation to costs and technical challenges, it was not without its limitations. This section will outline limitations from a primary perspective whilst carrying out this research and also limitations of the studies presented. To begin, gathering of data relating to the state of the cultured meat industry proved difficult because of the privacy of many companies. Due to the competitiveness of the market, it is fair to say that this research was unable to find detailed information relating to specific company projects, timelines and anticipated dates for market sale and any breakthroughs in the process, for example, media reformulations to reduce costs. This is perhaps a limitation in itself, as if companies were to share new findings and developments, this could potentially lessen the time it will take to commercialise cultured meat.

The next form of limitations related to industry and literature study limitations which have already been highlighted in the discussion section. To reiterate, some of the studies presented were perhaps optimistic in terms of the costing of cultured meat production (for example, CE Delft, 2021). While studies did a thorough analysis on several aspects of cultured meat production, one cannot account for every potential variable or additional expense without piloting at the scale in question. So, it is important to note that the figures presented are not concrete by any sense but rather an estimation. Further adding to the limitations, is that the figures presented render such a pilot too large of an investment just for trialling purposes. Therefore, research is limited to the companies who are currently operating in the cultured meat industry and as previously noted, do not tend to share findings.

5.2 Future work and Recommendations

This study shows that there is a vast amount of research and development required before cultured meat will be economically viable. It is of the upmost importance that media formulations are developed which contribute much less to the overall cost of production than they do currently. If this cannot be achieved, it is highly unlikely that cultured meat will be successful in the marketplace. The author recommends further research into plant hydrolysates and beyond soy hydrolysate as cheaper alternatives to amino acids. Perhaps other components need to be included in media formulations to counteract the difficulties posed by plant hydrolysate, particularly soy hydrolysate. Moreover, capital costs of bioreactors are high and have been shown to contribute significantly to costs. Perhaps with progress in the industry and more bulk purchasing of such equipment, the industry may see a decrease in costs. However, given the high level of sophistication of such equipment and specialist installation requirements, the industry may find a challenge in reducing these costs. Government grants and financial aids will be critical in contributing to the start-up capital to make cultured meat viable. Such financial aid will be form an important part of the piloting of cultured meat at an industrial scale. Until such pilots are conducted, one cannot be absolutely certain of costs of cultured meat production. More work must be done at government level to drive the scalability of cultured meat production.

In addition, without time constraints on this research, it would have been useful to conduct a detailed comparison relating to environmental impacts of cultured meat and conventional meat. Whilst this study focused on the techno-economics of cultured meat production, environmental considerations are a key factor in overall feasibility and of course, justification of cultured meat development. While this introduction touched on this topic, the author considers the matter of environmental impacts a ‘grey area’ with conflicting reports among scholars. Therefore, a further literature search in this area would have been beneficial.

Chapter 6 Conclusion

6.1 Conclusion

This research has shown that much progress has been made in the way of bringing cultured meat to the marketplace. The results section presents an increasing number of stakeholder companies in the industry, who are investing heavily in the scale up of cultured meat production. The industry has seen much success in producing a variety of cultured meat products from numerous different species. The issue now lies in producing these products in a cost-effective manor to benefit both producer and consumer. Therefore, to answer this research question bluntly, the author deems that cultured meat is not currently economically viable. However, findings from this research are promising, as it has clearly been identified that once the key cost drivers are lowered, cultured meat will be much more affordable to produce and for sale to the consumer. While these findings are encouraging, there is a vast amount of work, research and further development required for such targets to be met. Scholars have identified key areas for cost reduction and have presented many models and solutions for lowering costs. Several technical challenges which currently stand in the way of this must be overcome which will ultimately contribute to production cost reductions.

Chapter 7 References

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Appendices

Appendix 1

List of cultured meat companies, their country headquarters and founding year.

Company Name	Headquarters (Country)	Founding year
Ants Innovate	Singapore	2020
Aleph Farms	Israel	2016
Alife Foods	Germany	2019
Appleton Meats	Canada	2016
Artemys Foods	USA	2019
Avant Meats	China	2018
Balletic Foods	USA	2017
Because Animals	USA	2018
Biftek	Turkey	2018
BioFood Systems	Israel	2018
Bio Tech Foods	Spain	2017
Bluu Biosciences	Germany	2020
BlueNalu	Italy	2020
Boston Meats	USA	2020
Bruno Cell	Italy	2020
Cell Ag Tech	Canada	2018
Cell Farm Food Tech	Argentina	2019
CellMEAT	South Korea	2019
Cellular Agriculture Ltd	UK	2016
Cell X	China	2020
Clear Meat	India	2018
Cubiq Foods	Spain	2018
Cultured Decadence	USA	2020
Diverse Farm	Japan	2020
Finless Foods	USA	2016
Fork and Goode	USA	2018
Future Meat Technologies	Israel	2017
Gaia Foods	Singapore	2019
Good Meat	USA	2018
Gourmey	France	2019
Heuros	Australia	2017
Higher Steaks	UK	2018
Hoxton Farms	UK	2020
Innocent Meat	Germany	2018
IntegriCulture	Japan	2015

Lab Farm Foods	USA	2019
Like Foods	China	2020
Meatable	Netherlands	2018
MeaTech	Israel	2019
Memphis Meat	USA	2015
Mirai Foods AG	Switzerland	2019
Mission Barnes	USA	2018
Mosa Meat	Netherlands	2015
Mzansi Meat	South Africa	2020
New Age Meat	USA	2018
Orbillion Bio	USA	2019
Peace of Meat	Belguim	2019
Pristine Pet Food	USA	2020
Shiok Meats	Singapore	2018
SuperMeat	Israel	2015
VOW Food	Australia	2019
Wild Earth	USA	2017
Wild Type	USA	2017