A COMPARATIVE REVIEW OF CELL-BASED MARICULTURE AND CONVENTIONAL SEAFOOD LIFE CYCLE ASSESMENTS

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ABSTRACT

The global fishing and aquaculture industries inflict significant environmental impacts on our planet's oceans. The overfishing, pollution, and environmental degradation currently caused by these industries threatens the sustainability of marine ecological and industrial systems. Despite this, demand for seafood is expected to rise in the coming decades to service the growing global population with nutrient-rich foods. The difficulty in reconciling the need for drastic improvements in marine sustainability and the need to continue meeting global seafood demand has produced an interest in alternative solutions to seafood production. The emerging cell-based foods industry may hold the potential to produce seafood products with a major reduction in environmental and societal costs; however, the technology is incipient, and assessments have yet to be made regarding its efficacy at producing seafood with lower environmental impacts. In this review, we compare the environmental impacts of cell-based mariculture technology to those of the more conventional seafood production means of aquaculture and capture fishing. To accomplish this, we review and analyze the current slate of life cycle assessment (LCA) studies aimed at documenting the environmental implications of these respective fields. This approach involved selecting and filtering LCA studies of capture fishing, aquaculture, and cell-based mariculture. Climate impacts were assessed after studies were standardized per unit of production. The study's qualitative findings of environmental impacts and LCA shortcoming were reviewed and compared. Methodologies were also reviewed to allow for greater consideration of impact comparison. Overall, our findings suggested that cell-based mariculture may have higher global warming potential than capture fishing and aquaculture, due to its greater energy demands. However, cell-based mariculture outperforms capture fishing and aquaculture along most other dimensions of environmental impacts including diffuse, marine ecological impacts. We also discuss limitations posed by the current LCA methodologies in all three fields. LCA approaches to cell-based mariculture are limited by data quality and availability which engenders a greater reliance on assumptions. Capture fishing and aquaculture LCA methodology also struggle to standardize and incorporate the full range of fishery-specific impacts. Suggestions are made for greater research and assessment into LCA for all fields will be needed to appraise the full extent of environmental trade-offs.

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Chapter 1

INTRODUCTION

Global fish stocks have been increasingly fished at unsustainable levels with estimates placing the number of stocks being either overfished or fished at maximally sustainable levels at 93.8% (FAO, 2020). Poor management, pollution, and other environmental challenges have resulted in the decline of many fisheries (Hague et al., 2009). Despite this obstacle, demand for fish is expected to continue to rise in the coming decades (World Bank, 2013). Much of this demand will be met by the rapidly expanding aquaculture industry. Aquaculture farming and capture fishing both are associated with significant environmental and ethical problems; additionally, the success of these industries in meeting future demand will depend on the implementation of sustainable management practices (Merino et al., 2012). If sustainable strategies are not properly adopted, the implications could damage marine ecosystems and jeopardize the food and economic security of billions (Hauge et al., 2009). The United Nations outlined targets to end overfishing by 2020 through the recommended implementation of sustainable regulations and management practices (UN, 2015). These strategies have yet to generate the desired results (FAO, 2020).

A novel solution to meeting the future demand of seafood is cell-based mariculture. The technology of cell-based food utilizes in vitro cultivation of animal cells and tissue to produce consumable meat products (Rubio et al., 2019). Cells are cultured with the addition of nutritional inputs and grown into full-tissued meat through processing in bioreactors (Potter et al., 2020). This industrial production process avoids many of the issues that plague both fishing and aquaculture (Bhat et al., 2019). Although still in its infancy, the technology has the potential to become widespread (Hanga et al., 2020). Cell-based fish could serve as a replacement for the majority of the fish consumed in the future, taking pressure off of wild fish stocks and intensive aquaculture production. While the potential benefits of cell-based fish production are enticing, it is a nascent technology, and the full extent of its potential capabilities and deleterious effects are still being analyzed (Stephens et al., 2018; Tuomisto et at., 2011). The environmental and societal implications of a prolific cell-based fish industry are yet to be concretely understood.

Existing literature related to the technology has attempted to analyze the implications of cell-based agricultural production. Studies have attempted rudimentary life-cycle analyses on the product’s production (Mattick et al., 2015; Tuomisto et al., 2011); however, the extent of the environmental impacts will need to continue to be re-evaluated as the technology evolves from laboratory conditions to an industrial scale. Current analysis points towards energy use being the main environmental point of concern (Lynch and Raymond, 2019), an issue dependent upon the proportion of renewables in the supplying power grid. Research into the market feasibility of the cell-based mariculture industry has suggested that consumer acceptance (Bekker et al., 2017; Bryant et al., 2019; Van Loo et al., 2020) and regulatory approval (Bhat et al., 2019; Chriki and Hocquette, 2020) may be points of concern. Suggestions regarding product framing and legal strategies have been made (Bryant et al., 2019; Mohorcich and Reese, 2019). Additionally, the societal, ethical, and philosophical implications of producing and consuming cell-based meat are under debate; initial consideration points to ethical benefits for cell-based food, but the long term consequences are uncertain (Heidemann et al., 2020; Lee, 2018; Schaefer et al., 2014). Research is still in the process of comprehending and categorizing the impacts of an industrial cell-based meat and seafood industry.

Current research on the topic of cell-based meat has largely focused either on a general overview of the technology or specifically on cell-based meat replicating terrestrial animals, particularly beef. While the general analysis of cell-based meat provides a useful framework, understanding the impacts of cell-based mariculture in comparison to the impacts of conventional seafood production is essential to determining the efficacy of cell-based mariculture as an alternative foodsource. There is also a paucity of research into specific feasibility of cell-based mariculture technology related to technological, regulatory, and commercial dimensions. Additionally, existing research has focused on the abstract consequences of the technology; material conclusions regarding the cost-benefit tradeoff of encouraging a cell-based fish industry have not been made. This creates an opportunity for the creation of detailed policy and research recommendations regarding cell-based mariculture development and consumption based on comprehensive research and analysis of the topic.

Drawing on existing literature of the cell-based mariculture and traditional mariculture industries, this paper conducts a comprehensive review of the comparative socio-environmental implications of cell-based mariculture and conventional seafood production. From these findings, recommendations are made regarding what policy and research approaches to the technology and industry may be warranted. These conclusions may guide further necessary research into impact assessments of cell-based meat assisting researchers and industry participants. The comparative, cost-benefit analysis of cell-based fish will be used to make recommendations to policy-makers regarding the use of regulations and subsidies in the industry. Ultimately, the work of this paper will hopefully assist in developing a potential solution to the many problems facing seafood production and extraction.

Chapter 2

LITERATURE REVIEW

Existing research on the topic of cell-based foods has generated a detailed overview of the technology including its development and potential (Bhat et al., 2015; Jiang et al., 2020; Potter et al., 2020; Rubio et al., 2019; Stephens et al., 2018). It has also attempted to analyze the implications of cell-based foods adoption including the extent of its environmental impacts (Bhat et al., 2019; Lynch and Raymond, 2019; Mattick et al., 2015; Tuomisto et at., 2011). However, little research has focused on reviewing the concept of cell-based mariculture as a subset of overall cell-based food technology. As a result, an analysis of the environmental impacts and wider implications of cell-based seafood in comparison to conventional seafood production is absent from the current slate of literature. Conversely, cell-based production of terrestrial meats such as beef has attracted meaningful scientific efforts to analyze and compare cell-based impacts to those of livestock (Lynch and Raymond, 2019; Mattick et al., 2015; Tuomisto et al., 2011). Production processes for all forms of cell-based food are similar enough that this research may provide a rudimentary understanding of cell-based mariculture's potential impacts (Potter et al., 2020; Rubio et al., 2019). The current state of the global seafood industry, involving both fishing and aquaculture, contains its own unique set of problems and repercussions that can help to contextualize the impacts of a burgeoning cell-based mariculture industry. Existing research has attempted to compile the current extent of the seafood industry's impacts; however, little standardization exists within impact assessments of conventional seafood production.

This paper attempts to synthesize these existing fields of study to draw conclusions about the desirability of a potentially large cell-based mariculture industry serving as an alternative to conventional means of seafood production. To establish a broad understanding of the potential implications of greater adoption of cell-based mariculture, we review the technological potential, feasibility challenges, and socio-environmental impacts of the technology along with the current state of conventional seafood seafood production.

2.1 Fishing and Aquaculture

The global mariculture industry has seen substantial growth over the past several decades. Capture fisheries production has increased to 93 million tons while world aquaculture production has risen to 63 million tons (World Bank, 2013). The UN estimates the total value of marine resources at $3 trillion per year and 200 million jobs are tied to marine fisheries production worldwide (UN, 2015). This production supplies 16.6 percent of animal protein and 6.3 percent of all protein for human consumption; additionally, the rich nutrient composition of seafood makes it a vital resource for servicing dietary needs particularly in vulnerable populations (FAO, 2020; World Bank, 2013). Moreover, many types of seafood have been shown to perform better on environmental impact indicators than livestock sources of meat (Hilborn, 2018). With the global population expected to increase to 9 billion, seafood is expected to play an important role in providing food and nutrition. With the global population expected to increase to 9 billion, seafood is expected to play an important role in providing food and nutrition. Rising global incomes and consumer attitudes are also expected to further increase per capita demand in many regions of the world. Total fish supply is estimated to increase to 186 million tons by 2030 (World Bank, 2013). Reaching the level of production necessary to meet this demand poses challenges for the seafood industry.

Yields from fisheries are constrained by ecosystem productivity and management effectiveness. Over 90 percent of current global fish stocks are already being fished at unsustainable or maximally sustainable levels (FAO, 2020). Overexploitation coupled with additional environmental challenges such as pollution and climate change have damaged the productivity of many fisheries and, in some cases, resulted in complete fishery collapse (Hague et al., 2009). Research has demonstrated the importance of implementing sustainable fisheries management strategies to increase stocks (Merino et al., 2012; World Bank, 2013). If responsible management strategies are realized globally, then marine ecosystems may have the ability to sustain increased consumption rates; however, achieving this level of commitment to improved sustainability standards will be difficult. Proper enforcement of overfishing regulations is difficult for the fishing industry due to the geographic scale of the resource (Hague et al., 2009). Moreover, small-scale fisheries make up the bulk of the capture industry and developing countries account for a substantial portion of fish production (World Bank, 2013). Adequate management policy may be difficult to implement globally particularly in regions with weaker government institutions and informal industries. Difficulties have already spoiled the United Nations' Sustainable Development Goal 14.4 which calls for an end to overfishing as well as unregulated, illegal, and unreported fishing by 2020. Ecological and managerial obstacles have pushed the seafood industry towards the expanding alternative of aquaculture.

The past three decades have seen rapid growth in aquaculture; it now accounts for over 40 percent of seafood production. Due in part to the stagnation of wild fisheries production, aquaculture is expected to account for 60 percent of seafood production for human consumption by 2030 with it supplying the majority of the coming demand increases (World Bank, 2013). Research predicts that aquaculture should be able to meet its production goals. However, this success depends on the industry developing sustainably (Merino et al., 2012). Large-scale aquaculture production must contend with problems relating to fish feed, breeding, disease, processing, marketing and distribution (World Bank, 2013). Sustainable practices and business and technological innovation will be required for the industry to reach its potential.

Both marine capture fishing and aquaculture engender additional environmental externalities. Fishing fleets emit greenhouse gas emissions and other contaminants, and common fishing practices such as bottom trawling harm endangered marine species and disrupt ecosystems (Avadi and Freon, 2013; Ruiz-Salmon et al., 2021). Aquaculture also generates substantial amounts of waste from pesticide and antibiotic use, excess feed, and fecal waste, which pollutes neighboring aquatic ecosystems and endangers marine life; furthermore, the industry's use of wild caught fish as a major feed ingredient associates it with the problems of marine capture fishing (Bohnes et al., 2019; Pelletier et al., 2009). Sustainable management and development strategies such as closed system aquaculture and plant-based feeds can ameliorate some of these marine impacts; although these alternatives pose additional threats to sustainability through greater land and energy use (Philis et al., 2019).

Wider issues relating to ethics, health, and societal welfare also plague the seafood industry. Ethical concerns pertaining to fish treatment and slaughter surround both fishing and aquaculture. Research has found that animal welfare considerations are applied to fish much less than to other animals due in part to cultural distinctions; this differentiation has also led to a lack of research pertaining to welfare concerns in the mariculture industry (Kupsala et al., 2013). Levels of pollution in the oceans have also engendered health concerns for seafood consumption. The presence of mercury and other contaminants has been linked to health concerns in the form of neurocognitive damage and carcinogenic risks (Yokoo et al., 2003). These effects are most pronounced in vulnerable groups such as pregnant women, young children, and communities that consume fish at high rates. Analysis has found that substantial health risks to adults remain unproven; moreover, the nutritional benefits of fish have been found to outweigh potential harms (Du et al., 2012; Mozaffarian and Rimm, 2006). While the ultimate health consequences of fish consumption seem positive, it is unclear to what extent contaminant concentrations diminish the full extent of health benefits. Complete eradication of contaminant concentrations remains infeasible in marine capture fishing. The regulatory difficulties of the fishing industry have also precipitated a rise in labor violations. Fishing operations in developing countries are plagued by instances of forced labor (McDonald et al., 2020). Diffuse supply chains make accountability and enforceability for safe and legal practices difficult. Solutions for these broad sociological issues remain under-examined.

The challenges of the traditional mariculture industry in ethically and sustainably meeting global seafood demand will serve as a comparison for the challenges of cell-based mariculture. Cell-based mariculture provides a clear alternative to both fishing and aquaculture, one with a distinct set of impacts. Just as aquaculture has risen to fill increasing seafood demand, cell-based mariculture may prove to be a crucial production method that avoids the problematic aspects of both marine capture fishing and conventional aquaculture.

2.2 Technology Potential

Concerns related to the industrial production of animal products have spurred a rise in the prevalence of meat-alternatives. Producers of these alternatives have struggled to create plant-based alternatives with characteristics that closely mimic animal protein (Waschulin and Specht, 2018). The technology of cell-based agricultural production has the potential to create products that replicate the characteristics of traditionally produced meat without engaging in the problematic production processes present in the industry (Bhat et al., 2015). Moreover, the controlled artificial conditions used in call-based meat production engender great potential for manufacturing products with desirable nutritional, functional, or novel characteristics (Bhat et al., 2019).

These factors have encouraged the development of the cell-based meat industry over the past two decades. While the majority of this emerging industry is focused on producing replications of livestock meat, 20 percent of industry companies are focused on developing cell-based seafood products. These companies have publicly raised 49.5 million USD in the past five years, mainly in the form of venture capital (Choudhury et al., 2020). This reliance on venture capital and the investment cycle it creates poses risks for the sustained growth of the industry (Stephens et al., 2018). If scalability challenges associated with the technology become too costly, investment funding for the industry is at risk of declining. Additional support in the way of public funding and intellectual contributions from non-profits and universities could help the industry endure potential investment droughts and increase the likelihood of the technology coming to fruition (Stephens et al., 2018). Research has also indicated the importance of engaging stakeholders in the industry as they will play a large role in the future of the technologies' advancement (Jiang et al., 2020; Stephens et al., 2018). Detailed stakeholder analyses have yet to be carried out.

Cell-based mariculture's development has benefited from improvements in biomedical engineering and aquaculture techniques. Research has suggested that physiological characteristics of fish tissue may make it uniquely suited to in vitro cultivation (Rubio et al., 2019). Fish production can undergo more cell-doublings, is more stable, and, unlike terrestrial animal cell production, doesn't require the addition of CO_2 into its cultured environment; lean fish in particular are simple to produce and are widely consumed, widely studied, similar across species, and easily interchanged across products (Potter et al., 2020). Despite the promising potential of cell-based fish bioreactor cultivation, research in the field remains underdeveloped. Difficulties and unknowns germane to the large-scale development of cell-based fish will require additional research (Bhat et al., 2019; Choudhury, 2020; Rubio et al., 2019). The lack of a foundation of shared scientific knowledge between industry participants partly spurred by a lack of philanthropic research also remains an issue (Potter et al., 2020). Assistance in the form of expertise in interdisciplinary fields will also be vital to overcoming future challenges (Choudhury et al., 2020).

Achieving feasible development and scalability of cell-based mariculture is gated by numerous technological issues. Obtaining effective and appropriately priced cultured media and cell sources, mimicking the *in-vivo* myogenesis environment, and bioprocessing on a commercial scale are all unresolved challenges to the feasibility of a cell-based agricultural industry (Stephens et al., 2018). Research into innovations for scaling cell-based agriculture has been conducted revealing potential efficiency gains to be made through the use of microcarriers and optimal seeding densities (Bodiou et al., 2020; Hanga et al., 2020); however, recent research has yet to materialize into major technological advancement (Chriki and Hocquette, 2020). Industrial production levels remain far off, and problems relating to the nutritional and health quality of cell-based products remain unresolved. Additional research, investment, and collaboration may be necessary to surpass these barriers.

2.3 Legal and Regulatory Concerns

The cell-based mariculture industry must fit into a regulatory structure before it can provide its products on a commercial level. The novelty of cell-based agricultural products makes its exact legal and regulatory framework uncertain. Researchers have attempted to analyze the extent that regulatory setting and legal issues will be a concern. As cell-based fish will be a food product, its regulatory acceptance will likely come from food safety authorities (Bhat et al., 2019). In the United States, the USDA and FDA have already signed off on an agreement ascribing the roles of the respective food safety administrations in regulating cell-based foods (FDA, USDA, 2020). The safety standards required for government approval can be expected to be on par with existing standards for traditional meat production; the controlled production environment of cell-based agricultural products may be advantageous here as it could help avoid infection and contamination (Bhat et al., 2019). The production and supply chain of cell-based mariculture would still require a comprehensive review system to ensure safety; safety auditing throughout development and further research are also recommended (Bhat et al., 2019; Stephens et al., 2018).

Regulatory definitions and delineations of the involved production processes and components will play a large role in determining the pathways available to cell-based mariculture in different countries (Stephens et al., 2018; Waschulin and Specht, 2018). The production processes ultimately involved in industrial production of cell-based mariculture will also be of vital importance to the product's regulatory pathway (Stephens et al., 2018). Practices such as hormone growth promoters and genetic modification face additional regulatory scrutiny particularly in the European Union (Chriki and Hocquette, 2020; Seehafer and Bartels, 2019; Mohorcich and Reese, 2019).

The potential fate of cell-based agriculture's regulatory challenges have been further discussed in law journals. One recommendation has been made in favor of establishing a supplemental provision to the FDA's meat regulations as well as a generalized petition to determine the safety of future novel products and biotechnologies (Penn, 2018). Another cautions the FDA to adopt a philosophy of regulating novelty in addition to hazards, calling on the use of the public health safety net to regulate innovative technologies such as cell-based food (Tassel, 2013). One analysis recommends approaching cell-based food production either as the equivalent of a slaughterhouse or a drug manufacturing process; additionally, it recommends that more stringent regulations, based off of those in the Wholesome Meat Act and Food, Drug, and Cosmetics Act, be adopted to ensure complete safety (Schneider, 2013). All discussion on the topic remains speculation and advice as government regulatory agencies will ultimately decide on a framework. The extent to which the commercialization of cell-based mariculture succeeds will depend in large part on the actions of both regulatory agencies and the policy mechanisms employed by governments (George, 2019).

Another vital legal issue surrounding cell-based food concerns labelling rights. The ability for cell-based food producers to use familiar product labels will partially determine the future commercial viability of the technology (Bhat, 2019; Stephens, 2018). Under influence from the livestock industry, legal challenges have been levied at the right for plant-based meat and dairy alternatives to use traditional livestock food terms. These policies emphasize the importance of consumer protections in labeling products. In the EU, non-dairy products are forbidden from using terms such as 'milk' or 'cheese', a policy based on an EU regulation allowing states to adopt laws against misleading consumers (Tai, 2020). A proposal to further limit the use of meat terms such as 'burger' and 'sausage' was voted down by European lawmakers (Piper, 2020). In the United States, the Missouri District Court held up a regulation restricting the labeling of the word 'meat' to only apply to products derived from animal slaughter, rejecting the plaintiff's claim that the law violated the first amendment and prevented meat alternatives from making truthful statements about the characteristics of their products (Turtle Island Foods, SPC v. Richardson, 2018). Researchers have argued that, as cell-based food products will not be materially different from traditional meat products, they should be labelled with common names; it has been noted that the current regulatory framework in the US labels products based on the product's safety and composition not on the processes used in the product's production (Sforza, 2020). Meat-labeling has an extensive history in the US and EU, and confusion over meat terminology has been omnipresent (Tai, 2020). The topic of labelling will likely continue to be a contentious legal issue challenging the consumer success of cell-based mariculture products.

2.4 Consumer Acceptance

Provided that cell-based mariculture can become technologically feasible, affordable, and permitted by regulatory authorities, the industry will ultimately depend on favorable consumer attitudes to support commercialization. Research into the challenges of cell-based agriculture has suggested that this consumer acceptance may be problematic (Choudhury et al., 2020). The presence of negative perceptions and an aversion to unnatural food products could limit the market success of cell-based mariculture products (Chriki and Hocquette, 2020; Jiang et al., 2020). These negative perceptions are driven by concerns relating to taste and texture, artificiality, cost, health and safety, social ethics, and a mistrust of science (Tomiyama, 2020). Psychological research shows that naturalness perceptions develop from affective mechanisms such as disgust and fear rather than from analytic reasoning; the concept of naturalness is also found to be correlated with health and safety concerns over beliefs of genetic modification or chemicals (Wilkis et al., 2021). In line with these issues, research has found that consumers would heavily favor traditionally produced meat from animal slaughter over feasible meat alternatives including cell-based meat (Van Loo et al., 2020). These feelings were also present in highly educated consumers knowledgeable of the issues present in traditional meat production (Hocquette et al., 2015). A lack of animal welfare concerns for fish will likely make negative mariculture production impacts less salient, spurring fewer motivations for consumers to adopt cell-based mariculture (Kupsala et al., 2009).

Although cell-based meat does not seem likely to be favored by consumers, attitudes still show an openness to the technology. Studies have found that the majority of consumers support continued research into cell-based meat, and many would be willing to try products (Bryant et al., 2019; Hocquette, 2015; Van Loo et al., 2020). Favorable views are expressed at higher rates in China and India and among consumers with greater familiarity of meat alternatives, higher education, and greater trust in government food safety regulation (Bryant et al., 2019; Zhang et al., 2020). Media coverage may hold some responsibility for engendering greater acceptance of cell-based agriculture. Analysis of media coverage in the US and UK revealed a disproportionate presence of positive narratives over negative narratives; industry affiliated research was also shared more frequently than independent research or opposition opinions (Painter et al., 2020). This slant was found to be concerning as it leads to a lack of realistic, objective accounts of the state of the technology, and it risks a diminishment of public sentiment if media claims are not met.

Methods for supporting a greater acceptance of cell-based agriculture technology have been discussed by researchers. One proposed strategy consists of sharing information related to the sustainability benefits of cell-based food. Studies have suggested that sharing sustainability information can boost positive attitudes of cell-based meat, particularly in subjects unfamiliar with the benefits (Bekker et al., 2017; Van Loo et al., 2020). Consumer messaging has indicated to be successful at changing social norms, particularly when applied through a behavioral economics approach (Bhat et al., 2019; Tomiyama et al., 2020). Researchers have also identified the importance of consumer activism, the pressure that buyers exert on sellers, in affecting technology adoption, and recommendations have been made for focusing on the positive aspects of the technology instead of responding to negative perceptions (Mohorcich and Reese, 2019). Research into the effect of naming on consumer acceptance has shown substantial differences in attitudes between names; using terms such as ‘clean meat’ to describe cell-based meat were viewed much more favorably than terms such as ‘lab-grown meat’ (Bryant and Barnett, 2019). These findings corroborate the psychological research demonstrating the importance of emphasizing health and safety associations over providing analytical information.

Researchers vocalized the need for additional research to fully understand consumer attitudes and develop innovations to assuage consumer concerns. Some researchers critiqued the research focus on consumer acceptance, insisting that success in cell-based agriculture commercialization will ultimately be driven by complex social apparatus and government policies that emphasize supportive tax and subsidy regimes (Stephens et al., 2018).

2.5 Social and Ethical Impacts

The potential cell-based mariculture industry will have significant ethical and societal implications. Cell-based agricultural products are considered to be ethically superior to their traditionally produced counterparts (Bhat et al., 2019; Schaefer et al., 2014). The in vitro production practice will lack a nervous system, averting any possibility for suffering; although, current production methods utilize biopsies on animals to collect initial cells requiring some amount of animal exploitation (Chriki and Hocquette, 2020). As a whole, the lack of animal slaughter and industrial farming conditions that animals are kept in for traditional meat and fish production makes cell-based meat a superior alternative ethically (Heidemann et al., 2020; Schaefer et al., 2014). Further societal benefits are expected from a transition from a traditional meat and seafood production system to cell-based agriculture including a decline in zoonotic disease risk (Bhat et al., 2019).

There is great difficulty in anticipating the full extent of the practical and philosophical consequences of meaningful adoption of cell-based mariculture technology. Researchers have attempted to analyze the potential ethical objections brought about by cell-based meat including: that in vitro meat is disrespectful to nature or animals, that it will result in fewer happy animals in the world, and that it may lead to forms of cannibalism. The analysis concluded that these objections were not convincing enough to caution against cell-based meat development. (Schaefer et al., 2014). Additionally, research has suggested that proliferation of cell-based food products in the marketplace may lead to societal reexamining of our relationships with food, with our environments, and with animals (Weele and Driessen, 2013). Utilitarian, deontological, and virtue ethical principles also imply that a slaughter free meat chain could have significant impacts on our relationships with animals; slaughter free meat products could diminish desensitization of animals and lead to further ethical gains (Heidemann et al., 2020). The extent to which this philosophical change would apply to fish is unclear; most research has focused on the implications of reducing livestock slaughter. Fish make up the majority of consumed vertebrates. Due to fish's lower perceived ethical standing and the smaller health gains to be made from cell-based fish production, it has been hypothesized that fish will be a lesser target for replacement (Heidemann et al., 2020; Kupsala et al., 2013). Concerns have been raised over the potential unintended consequences of cell-based meat adoption. As the early stages of ethical discourse will significantly influence public and social acceptance and policy and regulatory design, approaching the topic with cautious deliberation and critical evaluation is crucial for ensuring that the technology will serve the values and principles that society wants to uphold (Lee, 2018). The downstream societal effects of the ethical and philosophical changes brought about by cell-based food are unknown; it is important that attempts to understand these implications continue to develop along with the industry.

2.6 Environmental Impacts

The environmental and sustainability concerns of traditional meat production are perhaps the largest motivating factor for the development of cell-based agriculture. While the environmental impacts of livestock and mariculture industries are well-studied, a comprehensive picture of the environmental costs of cell-based food products has not yet formed. Studies have attempted to approximate potential environmental impacts by conducting life cycle assessments of these products (LCAs). Life cycle assessment methodologies allow for a systematic analysis of a product’s environmental impacts over the products life cycle. Conducting LCAs for an emerging technology is difficult due to the uncertainties inherent in describing its production. Cell-based agricultural technology is currently not at an industrial level, and it will continue to undergo changes in production techniques. Researchers have attempted to develop a framework for upscaling nascent technologies in ex ante LCAs based on previous LCA literature. The devised framework consists of: projected technology scenario definition, preparation of a projected LCA flowchart, and projected data estimation (Tsoy et al., 2020). The researchers recommended incorporating different kinds of expertise from technology experts into *ex ante* LCA.

Previous LCAs of cell-based agriculture technology have demonstrated common trends (Jiang et al., 2020). Cell-based food production seems to be far superior to livestock production in regard to agricultural inputs such as water and in land use; however, cell-based meat was found to have emission impacts derived from high rates of energy use (Lynch and Raymond, 2019; Mattick et al., 2015; Tuomisto et at., 2011). These emissions have led cell-based meat to have a higher global warming potential than pork and poultry though not beef (Mattick et al., 2015). The degree of impact from energy generation is heavily conditioned on the degree of decarbonization present in the supplied energy. In LCA scenarios with substantial decarbonized energy use, long-term emissions are substantially less (Lynch and Raymond, 2019). Cell-based meat performed worse than other plant-based meat alternatives in comparative life cycle analyses due in large part to its higher energy demand (Jiang et al., 2020; Smetana et al., 2015).

The results of these *ex-ante* LCA depend heavily on the assumptions made for the production process. Greenhouse gas emissions were found to range significantly due to the diversity of production systems and inputs used in calculations (Jiang et al., 2020). As the technology will continue to develop in regard to production systems, inputs, and energy efficiencies, current LCAs are plagued by uncertainties. It is established that frequent LCA research should be carried out as production understandings increase (Mattick et al., 2015). Moreover, the existing research emphasizes the importance of fully understanding the environmental consequences and trade-offs of the technology before production is scaled to major industrial levels. No previous LCAs have specifically analyzed the environmental impacts of cell-based mariculture, nor have they compared the impacts to those of the marine capture or conventional aquaculture industry.

2.7 Gaps and Conclusions

Cell-based mariculture has the potential to hold immense improvements environmentally and ethically. The technology will have to contend with numerous challenges regarding industrial development, government regulation, and consumer acceptance. Solutions to these problems will require further research and innovation. The novelty of cell-based mariculture makes the full extent of its impacts unclear, further emphasizing the importance of continued research and theorizing. The traditional mariculture industry has substantial, intractable problems that adoption of cell-based mariculture could alleviate; however, research into the comparative impacts of cell-based and conventional seafood production is currently lacking. Ultimately, a clear picture of the cost and benefits of industrial production of cell-based mariculture is not present, limiting the ability for policy-makers and stakeholders to make relevant decisions.

Chapter 3

METHODS

To address the aforementioned research gaps regarding cell-based mariculture's comparative impacts, this paper employs a structured methodology consisting of two main phases. The first phase involves the search for and selection of literature to use in the comprehensive review, and the second phase categorizes and analyzes this research to generate results.

1.1 Literature Selection

The tool of life-cycle assessment has been increasingly utilized in research to compile and standardize the environmental effects of various production systems including those of incipient technologies; therefore, LCA provides an ideal source for analyzing and comparing the impacts of different means of seafood production (Mattick et al., 2015; Ruiz-Salmon et al., 2021, Tsoy et al., 2020). Thus, this review seeks primarily to address LCA studies applied to the sectors of cell-based food production, capture fishing, and aquaculture.

The literature search focused on journal publications published within the last two decades. Prior to 2000, life-cycle analyses were less commonly employed in research, and the production processes for all three sectors have evolved significantly in recent years. Literature searches were conducted through several research databases: most significantly, ScienceDirect, AGRICOLA, Public Library of Science, and Google Scholar. Publications were limited to journals accessible through Cal Poly's library web-search facilities. To collect the broadest swath of relevant literature, multiple topic searches were conducted with different keywords and phrases. Principal searches were conducted with the term 'life cycle assessment' combined with 'cell-based seafood', 'cell-based meat', 'seafood', 'fishing', and 'aquaculture'. Articles yielded from these searchers were preliminarily filtered based on relevance and status. Only peer-reviewed journal publications were selected, and publications outside the subject areas of natural resources and life cycle assessment were excluded. The reference manager software Mendeley was utilized to log the selected publications.

We then reviewed LCA-related publications addressing the three targeted sectors of seafood production: cell-based, fishing, and aquaculture. Many of these studies were pulled from recent LCA reviews of fisheries (Avadi and Freon, 2013; Ruiz-Salmon et al., 2021) and aquaculture (Bohnes et al., 2019; Henriksson et al., 2012; Philis et al., 2019) methods, and the aggregate findings of these reviews are also addressed in the discussion. Because the number of studies analyzing the life cycle impacts of cell-based production are limited and there are currently no LCAs specifically targeted at cell-based mariculture production; this paper relies on LCAs that have more broadly analyzed cell-based food as a proxy for cell-based mariculture. The processed used throughout the cell-based food industry, and the resulting impacts of these products, are expected to be largely analogous, although cell-based mariculture technology may rely on a lower demand for heating and cooling due to the characteristics of fish tissues (Rubio et al., 2019).

This preliminary review was used to further differentiate publications based on the quality and applicability of their LCA methods and comparability of their results. Several studies were ultimately excluded from the review due to incongruities within their life cycle assessment methodologies that made cross-sector comparison infeasible. The reviewed publications all contained LCAs that tracked similar impact indicators across similar system boundaries that ended at the gate of landed, pre-processed fish.

1.2 Literature Analysis

The selected studies were reviewed based on the four phases provided under the International Organization for Standardization (ISO) LCA standard: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. These phases act as the guidelines for LCA methodologies and analyses. This approach enabled us to document the most pertinent aspects of the reviewed LCAs including system boundaries, functional units, assumptions, data sources, impact categories, and LCIA results. The methodological characteristics, LCI, and LCIA results of the publications were recorded in Excel. To allow for comparison, functional units were standardized to 1 Tonne of landed fish, live-weight fish, or cultured meat.

For the LCIA data, comparisons were primarily conducted for the principal impact category of global warming potential (GWP) followed by other common categories such as eutrophication (EP), acidification (AP), cumulative energy demand (CED), and land and water use. Although comparability between results is difficult due to variance in methodological parameters, consistency was increased by limiting the reviewed LCAs to those using cradle-to-gate systems, from extraction to delivered fish, producing a functional unit of live-weight or landed fish. All analyzed studies were also categorized by the type of production or extraction method used in producing seafood. Fishing LCAs were differentiated between trawling and purse-seining techniques, and aquaculture was differentiated between closed and open systems. The wider context of the LCIA results were incorporated into the comparative analysis of the studies' impacts.

Chapter 4

RESULTS

4.1 Methodology Analysis

4.1.1 Capture Fishing Methodologies

Life cycle assessment studies on capture fisheries have substantial methodological variance. This lack of standardization is in part due to the diversity of fisheries analyzed. The included studies varied in fish species studied, fishing method observed, and geographic region. Previous research has highlighted that capture fishing LCA results vary significantly relative to type of species analyzed with larger palegic fish generally performing better than large pelagic fish (Hilborn, 2018). This analysis includes studies primarily focused on large pelagic fish such as tuna as the assessment methodologies for these fisheries best lended themselves for cross-field comparison due to their similarity in functional units and system boundaries. Trawling and purse seining were the dominant extraction methods for these fisheries. Regionally, the studies were most heavily concentrated in the North Atlantic while some studies assessed fisheries across the Atlantic, Pacific, and Indian Oceans (Table 2). It is notable that studies focused on fisheries in proximity to East Asia are largely absent from this review and the literature in general; although the region is responsible for a predominant amount of global seafood production, LCA is utilized much less as a research tool (Avadi and Freon, 2013).

The selected LCA studies had cradle-to-gate system boundaries limited to unit processes within the extraction phase of capture fishing. Under this delineation, the studies defined their functional units as a quantity of fish landed in port generally measured in tons or kilograms. Within the extraction phase, studies varied on the exact processes included within their analysis. All studies included at minimum the use and maintenance of the fishing vessels. Processes beyond the extraction phase such as fish processing, transportation, and end of life were not considered as they were outside the given scope of these studies.

The slate of impact categories included within the studies' respective LCA inventories also varied (Table 1). Every study included a category relating to global warming potential while other common categories such as acidification, eutrophication, ozone depletion, and eco-toxicity were addressed in a minority of studies. The reviewed LCAs also attempted to discuss fishery-specific impacts qualitatively, outside of the structured LCA methodology. These impacts, which included species removal, sea use, and seafloor disturbance, do not currently have accepted LCA approaches, thus they were absent from the main impact descriptions. Recommendations have been made for the inclusion of such fishery-specific impact categories to more accurately reflect the supply chain impacts of seafood; however, current LCAs have attempted to address these issues qualitatively (Ruiz-Salmon et al., 2021).

Table 1: Frequency of use of different impact categories in LCA studies by field

Impact Category	Fishing	Aquaculture	Cell-based
Global Warming Potential	7	6	4
Acidification Potential	2	6	2
Eutrophication Potential	2	6	2
Cumulative Energy Demand	0	6	4
Ozone Depletion Potential	3	0	1
Human Toxicity	3	1	1
Marine Ecotoxicity	3	2	0
Terrestrial Ecotoxicity	0	1	0
Abiotic Depletion Potential	1	1	0
Biotic Depletion Potential	0	4	0
Water Use	0	3	1
Land Use	0	1	4

4.1.2 Aquaculture Methodologies

Similarly to capture fishing, aquaculture LCAs vary substantially in their methodological approaches. A diversity of species farmed and technologies used also inhibits synthetization of aquaculture methods and impacts. As with capture fishing, LCA results vary greatly relative to type of species targeted (Hilborn, 2018). The included studies primarily focused on aquaculture operations of diadromous and freshwater finfish such as salmon and trout (Table 2). These kinds of species provide the closest comparison to the kinds of fish products generated through capture fishing and cell-based production; however, they alone are not representative of the global aquaculture industry which is proportionally made up of notable amounts of crustacean and mollusc farming and a relatively low amount of salmon farming (Bohnes et al., 2019). These analyzed operations were located mainly in Europe, North America, and Chile, roughly reflecting the concentration of global salmon and trout production (Philis et al., 2019). As with capture fishing LCAs, there exists a lack of aquaculture LCAs carried out in Asia where approximately 90% of aquaculture production occurs (Bohnes et al., 2019). The studies included different aquaculture methods spanning open and closed systems and land and sea-based systems with the most common techniques being net pen, sea cage, recirculating, and flow-through. The aquaculture operations analyzed in the studies were further varied due to differences in feed composition and conversion. Issues of data quality have been raised by previous reviews corresponding to difficulties in obtaining accurate data sources (Henriksson et al., 2012).

The aquaculture LCAs analyzed unit processes within the system boundaries of the farming phase; functional units generally consisted of 1 ton of live weight fish at the farm gate. As with capture fishing LCAs, aquaculture LCA's choice of functional unit and system boundary omitted any supply-chain impacts beyond the initial phase of fish production such as processing, product transportation, and end-of-life. Additionally, the aquaculture LCAs refrained from analyzing the impacts of infrastructure, a common choice due to the difficulty in calculating infrastructure inputs compared to the small impacts they bear (Henriksson et al., 2012; Philis et al., 2019). Previous reviews have highlighted that infrastructure may contribute between 0% and 19% of aquaculture impacts within the indicators of global warming, eutrophication, and acidification (Henriksson et al., 2012). Processes related to chemical use, equipment, and effluent treatment were also largely absent from the studies. The main processes included within analyses related to feed production, fish production, transport, hatchery, effluent, and energy supply.

The impact categories included within the aquaculture LCAs most commonly centered around global warming, acidification, eutrophication, and cumulative energy demand (Table). Additional categories included human and marine toxicity, biotic resource use, and land and water use. Aquaculture studies are beset by the same methodological issues as fisheries studies regarding the involvement and calculation of aquaculture-specific impacts such as biotic resource depletion and marine ecotoxicity. Although many studies made attempts at incorporating these impact categories, methodologies for their analyses differed (Henriksson et al., 2012). Ancillary impacts such as the introduction of invasive species by way of escapes, the spread of diseases, genetic pollution, and seafloor disturbance were also omitted from quantitative analyses despite their identification as serious concerns (Pelletier et al. 2007; Philis et al., 2019).

4.1.3 Cell-based Methodologies

Anticipatory life cycle assessments of cell-based food production are currently still limited in number and scope (Mattick et al., 2015; Sinke and Odegard, 2021; Tuomisto et al., 2014; Tuomisto and Teixeira de Mattos, 2011). Cell-based food production is a novel technology undergoing frequent development; moreover, the field is composed of numerous parties pursuing the commercialisation of the technology with different production systems and employed inputs. This absence of a working, commercial-scale process to base LCA studies on has contributed to a large degree of uncertainty in cell-based LCAs as studies must make assumptions about hypothetical production processes. Studies mainly utilize simulation models, literature, and mathematical formulas to base analysis on. This issue is exacerbated by a lack of data availability for LCA studies due to the lack of publicly available technical information of cell-based production.

Current studies on cell-based LCAs have focused on analyzing and comparing cell-based meat to conventional livestock production. No studies have been conducted specifically targeted at cell-based seafood production although a recent report has included cell-based mariculture companies in its data set (Sinke and Odegard, 2021). The processes used in the production of cell-based fish and meat are similar although there may be some discrepancies particularly in regard to heating and cooling demand (Rubio et al., 2019).

Cell-based LCAs utilize functional units of 1 kilogram of cultured meat biomass. The characteristics of this meat vary between studies reflecting the production processes assumed by the LCA practitioners. System boundaries for studies used a cradle-to-factory approach including the processes of nutrient media productions and cell cultivation. Beyond these main activities, the studies varied in what processes they included with facility cleaning and energy requirements being omitted by Tuomisto and reactor production being excluded by Mattick. The main impact categories addressed in the studies related to global warming, cumulative energy demand, and land and water use while acidification, eutrophication, and ecotoxicity were included less frequently (Table 1).

4.2 Impact Results

4.2.1 Capture Fishing Results

The most significant impact areas recorded in the reviewed LCA studies were related to the use of fishing vessels with the largest source of environmental impacts coming from vessel fuel use. The efficiency of fuel consumption and the degree of environmental effects caused by its use were influenced by the type of fishing gear utilized, with trawling operations performing as the most intensive, the quality of the fuel, and an array of complex factors related to the efficiency of fishing fleets such as stock status and crew experience. Additional impacts were traced to the vessel maintenance phase where the use of antifouling materials and refrigerants contributed to toxicity. Impacts from ancillary phases such as construction and end-of-life were often omitted from the selected analyses, although previous reviews have suggested that the impacts from these phases are negligible in comparison to vessel use and maintenance (Ruiz-Salmon et al., 2021).

Despite not fitting into accepted LCA methodologies, fishery-specific impact categories such as by-catch, discards, and seafloor disturbance were identified in most studies (Figure 1). The lack of an LCA framework precluded the generation of quantitative findings; however, reviews have described these impacts as notable areas of environmental concern particularly given their relation to marine biodiversity loss (Avadi and Freon, 2013). Previous reviews have also suggested the incorporation of marine plastic debris related impacts caused by derelict and loss fishing gear although no operational methods for this kind of impact currently exist (Avadi and Freon, 2013).

The constraints of accepted LCA methodologies prevent the complete quantitative documentation of capture fishing impacts. The aforementioned fishery-specific impacts must be considered when evaluating the repercussions of seafood production to allow for accurate comparisons. Nevertheless, the included study's LCA results do provide a concrete picture of the direct consequences of capture fishing activities on climate change.

4.2.2 Aquaculture Results

Based on the reviewed studies (Table 2), the most significant aquaculture impacts were related to the fish farming stage, feed production, and energy supply systems. Farming was associated with driving eutrophication and water dependence impacts. Feed production was associated with driving energy demand, biotic resource use, acidification, and climate change impacts. Energy supply systems were also associated with driving cumulative energy demand and climate change impacts. The impacts of feed production and energy supply systems were variable as they reflected the discrepancies in feed conversion ratio and electricity requirements respectively. Large variations were present between the highest and lowest impacts scores for many categories; previous reviews have cautioned that these discrepancies are likely due to the different methodological choices in aquaculture LCAs, a characterization that has made meta-analysis difficult (Bohnes et al., 2019).

Different aquaculture systems also varied in their scores. Closed sea-based systems such as sea cages performed the best in global warming and acidification indicators while closed land-based recirculating systems performed the worst. Closed systems performed much better than open systems for eutrophication impacts while open and sea-based systems performed better than closed and land-based systems respectively at cumulative energy demand. Although aquaculture LCAs struggle to calculate aquaculture specific impacts such as the biodiversity threat posed by escapes and genetic pollution, studies suggest that open and sea-based systems are more responsible for these burdens. These disparities further prevent the synthesis of aquaculture impact results; each system of aquaculture production has varying advantages and disadvantages corresponding to greater burdens on different impact categories.

For all aquaculture systems, and most impact categories save for eutrophication, feed production was the predominant source of environmental burdens. Conventional aquafeed is partially composed of fish meal and fish oil sourced from wild caught fish; this condition subjects aquaculture LCAs to many of the same impact results and methodological issues as capture fishing in regard to calculating the repercussions of impacts such as species removal and seafloor disturbance. The impact scores of feed production processes varied substantially, in part due to these methodological difficulties, and in part due to notable differences in feed composition, where different ingredient mixes can have different environmental costs, and feed conversion ratios.

As with capture fishing LCAs, the lack of a standardized framework for incorporating the full range of aquaculture impacts hinders any quantitative analysis of aquaculture LCA results. Poor data quality and methodological and operational variance also hamper attempts at summarizing aquaculture LCAs into binary results. However, the included studies do illustrate what the slate of aquaculture impacts may be (Figure 1).

4.2.3 Cell-based Results

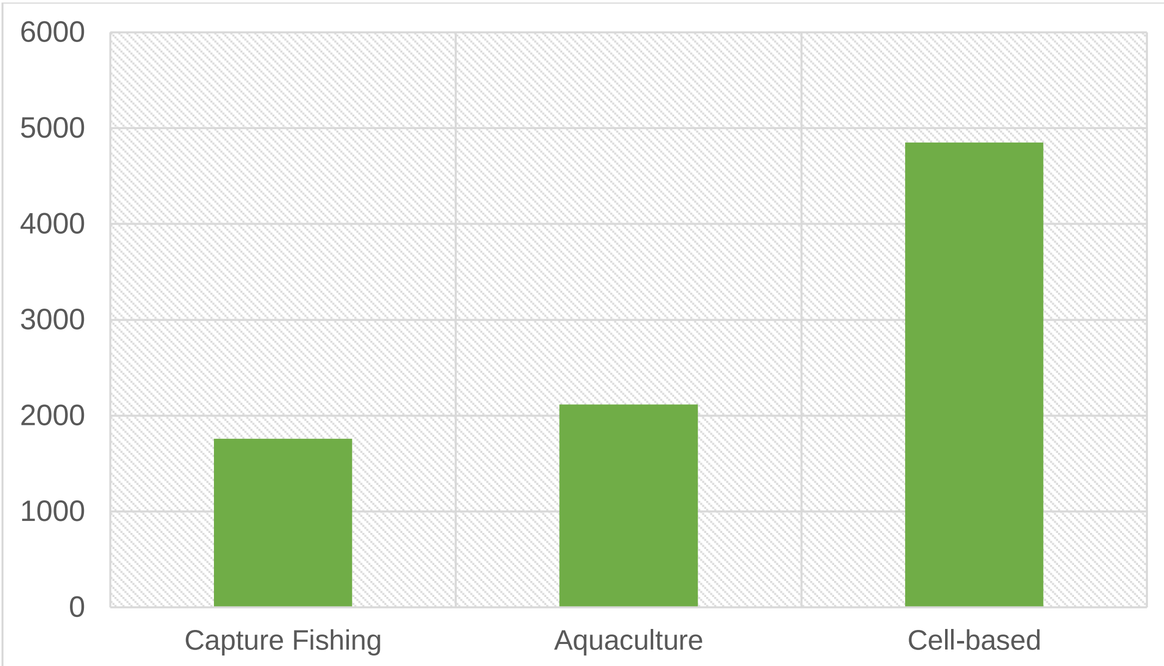
Cell-based LCAs experienced a range of differing impact results owing to the variance in methodologies and production assumptions. Studies have identified that the energy use required for the production and heating of growth mediums would likely account for the largest contribution to environmental impacts. Following energy use, the production of medium ingredients posed the next most significant burden. The impacts of cell-based LCAs primarily fell within the categories of global warming potential and cumulative energy demand while land and water use impacts, related to feedstock production and cell cultivation respectively, made up smaller but notable contributions. Impacts to remaining LCA inventory categories were largely negligible (Figure 1).

The continued development of cell-based production into an industrial scale will continue to change its resulting impacts. Due to a lack of data and the reliance on assumptions and experimental models of development, these LCA studies operate on a degree of uncertainty that may cause impacts to appear higher than they might be under industrial scale processes (Scharf et a., 2019). Improvements in energy efficiency, adoption of different energy sources, increased medium efficiency and better composition, and improved supply chain collaboration are all possible directions for cell-based production; these advancements would curtail the environmental impacts of cell-based production and reduce the relevance of previous LCA studies.

Further consideration must be made toward the lack of LCA studies addressed specifically at cell-based mariculture technology. Research into the feasibility of cell-based fish production has suggested that cell-based fish may involve slightly lower energy demands due to favorable differences in metabolic processes and temperature ranges between fish and livestock tissue (Potter et al., 2020). Regardless of these uncertainties, it is expected that cell-based mariculture production techniques will closely align with conventional cell-based operations (Rubio et al., 2019).

Figure 1: Categories of notable impact areas attributable to each production type

Figure 2: Median Global Warming Potential (kg CO2 eq) contributions from 1 metric ton of fish biomass



4.3 Cross-Field Impact Comparison

There are many limitations to directly comparing the environmental impacts of cell-based, wild caught, and farmed seafood. All three approaches pose problems for accurate and complete life cycle assessments. The diversity of practitioners, methods, species, and geography in these industries poses a challenge to any attempt to summarize the respective impacts of these industries into digestible and comparable, quantitative results. The methodological diversity within the body of LCA literature applied to these approaches further inhibits synthetization. Variations in system boundaries can lead to dramatically different results. LCA as an existing tool also falls short at encapsulating the full range of capture fishing and aquaculture' diffuse impacts to issues such as biodiversity loss, seafloor disturbance and plastic pollution. Additionally, the lack of standardization within LCA approaches to these industries and limitations of data quality and availability engenders a greater reliance on assumptions which in turn dilutes the accuracy of LCA findings. For these reasons, a comparative review of the respective impacts of these industries must rely heavily on qualitative findings for comparison.

Given the discrepancies in LCA impact category inclusion, direct result comparison remains infeasible for most impacts. However, global warming potential (GWP) does occur as an impact category in virtually every reviewed LCA across the three approaches. Considering the importance of curbing climate change impacts within food systems, a direct comparison across this category may be of use. In Table 2, GWP results of selected LCAs are tabulated with their functional units standardized to 1 T of landed fish, live weight fish, and cultured meat respectively. Despite the variance between individual studies, cell-based meat tends to perform the worst in GWP while capture fishing is generally associated with the lowest climate impacts (Figure 2). Aquaculture performs slightly worse than capture fishing; however, aquaculture GWP impacts are highly dependent on the production method with recirculating systems performing much worse than open systems.

These findings reflect previous attempts to assess and compare the environmental impacts of cell-based meat production (Lynch and Raymond, 2019; Mattick et al., 2015; Sinke and Odegard, 2021; Tuomisto et al., 2014); the high energy demands of cell-based production translate into large life cycle climate emissions. The relatively smaller emissions footprint capture fishing also corresponds to previous cross-field LCAs (Hilborn, 2018). However, as stated previously, these results are contingent on a variety of assumptions about the development of cell-based production, and there are expectations that the actual impacts will change and lower as cell-based production develops into an industrial scale (Scharf et a., 2019). Of particular importance is the potential for cell-based production to incorporate a sustainable energy mix that would dramatically shrink emissions (Sinke and Odegard, 2021).

While cell-based production may perform worse than conventional seafood production in regard to climatic impacts and energy demand, LCA findings suggest that it may perform better in most other categories. Cell-based impacts on all other categories save for global warming, energy demand, and land and water use are considered negligible (Sinke and Odegard, 2021). Conversely, capture fishing and aquaculture operations were found to appreciably contribute to a litany of environmental impacts including eutrophication, acidification, human and ecotoxicity, and biotic depletion (Figure 1). Studies further highlight the range of environmental burdens posed by these industries that are too difficult to incorporate into LCA findings (Avadi and Freon, 2013; Bohnes et al, 2018; Henriksson et al., 2011; Philis et al., 2019; Ruiz-Salmon et al., 2021). Capture fishing and aquaculture both threaten marine health and biodiversity through habitat destruction, species depletion, plastic pollution, genetic pollution, escapes, and disease. Although these impacts are difficult to quantify, they pose considerable threats to marine sustainability.

Table 2: Global Warming Potential scores from capture fishing, aquaculture, and cell-based meat life cycle assessments

Study	Species	Method	Region	FU	GWP (kg CO2 eq)
Eyjolfsdottir et al (2003)	Cod	Trawling	Northeast Atlantic	1 T Landed Fish	1760
Hospido and Tyedmers (2005)	Tuna	Purse Seining	Atlantic, Pacific, Indian	1 T Landed Fish	1800
Guttormsdottir (2009)	Cod	Trawling	Northeast Atlantic	1 T Landed Fish	5140
Iribarren et al (2010)	Tuna	Purse Seining	Atlantic, Pacific, Indian	1 T Landed Fish	1530
Vasquez-Rowe et al (2010)	Mackerel	Trawling	Northeast Atlantic	1 T Landed Fish	2278
Avadi et al (2014)	Anchovies	Purse Seining	Pacific	1 T Landed Fish	770
Parker et al (2015)	Tuna	Purse Seining	Atlantic, Pacific, Indian	1 T Landed Fish	1140

Ayer and Tyedmers (2009)	Salmon	Net Pen	Canada	1 T Live-Weight Fish	2073
Ayer and Tyedmers (2009)	Salmon	Marine Bag	Canada	1 T Live-Weight Fish	1900
Ayer and Tyedmers (2009)	Salmon	Flow-Through	Canada	1 T Live-Weight Fish	2770
Ayer and Tyedmers (2009)	Salmon	Recirculating	Canada	1 T Live-Weight Fish	28200
Ayers et al (2016)	Salmon	Net Pen (CAM)	Chile	1 T Live-Weight Fish	2210
Ayers et al (2016)	Salmon	Net Pen (Nylon)	Chile	1 T Live-Weight Fish	2660
Abdou et al (2017)	Seabass	Sea Cage	Tunisia	1 T Live-Weight Fish	3182
Aubin et al (2009)	Trout	Flow-through	France	1 T Live-Weight Fish	1917
Aubin et al (2009)	Seabass	Sea Cage	Greece	1 T Live-Weight Fish	253
Aubin et al (2009)	Turbot	Recirculating	France	1 T Live-Weight Fish	4828
Boissy et al (2011)	Salmon	Sea Cage (ST Diet)	France	1 T Live-Weight Fish	1660
Boissy et al (2011)	Salmon	Sea Cage (ST Diet)	France	1 T Live-Weight Fish	1960
Boissy et al (2011)	Trout	Sea Cage (LFP Diet)	France	1 T Live-Weight Fish	1540
Boissy et al (2011)	Trout	Sea Cage (LFP Diet)	France	1 T Live-Weight Fish	1450
Pelletier et al (2009)	Salmon	Net Pen	Norway, UK, Canada, Chile	1 T Live-Weight Fish	2160
Sinke and Pelle (2021)	In Vitro Biomass	Cultured (Conventional Energy)	N/A	1 T Cultured Meat	14000
Sinke and Pelle (2021)	In Vitro Biomass	Cultured (Sustainable Energy)	N/A	1 T Cultured Meat	2000
Mattick et al (2015)	In Vitro Biomass	Cultured	N/A	1 T Cultured Meat	7500
Tuomisto and de Mattos (2011)	In Vitro Biomass	Cultured	N/A	1 T Cultured Meat	2200

Chapter 5

DISCUSSION

Rising global seafood consumption necessitates new approaches towards seafood production such as cell-based mariculture. However, balancing these production needs with efforts to improve the state of fisheries and usher in greater sustainability poses a significant challenge (UN, 2015). To evaluate the environmental burdens posed by seafood production methods, LCA studies have emerged as a critical tool to document impacts and compare production systems. By comparing LCA analyses of cell-based mariculture and conventional means of seafood production, we have found that cell-based mariculture is not strictly superior in measures of environmental impacts. Encouraging cell-based production over conventional means poses environmental tradeoffs that must be considered to assess the viability of this technology in improving seafood production’s sustainability. This review has identified the main points of comparison across LCA results as well as the main methodological considerations necessary to frame these results.

Our analysis indicates that the energy demands of cell-based mariculture production result in this approach having higher global warming potential impacts than both capture fishing and aquaculture. However, cell-based production remained largely free of notable contributions to most other impact categories. Capture fishing and aquaculture were both associated with a wider range of environmental impacts to categories including eutrophication, acidification, human and ecotoxicity, and biotic depletion. Additional environmental externalities beyond the usual scope of LCA such as habitat destruction, plastic pollution, and genetic pollution were also attributed to capture fishing and aquaculture operations.

These comparative LCA results reflect previous research into the environmental effects of cell-based agriculture technology. Previous LCA attempts (Lynch and Raymond, 2019; Mattick et al., 2015; Sinke and Odegard, 2021; Tuomisto et al., 2014) have identified cell-based production’s energy demands as the largest challenge to the industry’s sustainability potential. However, these findings reflect the uncertainties of a nascent technology. As cell-based production continues to develop, and as the industry adopts more sustainable energy mixes, the environmental costs of cell-based mariculture production may decrease significantly from these initial findings (Scharf et a., 2019). While these prior studies have suggested that cell-based production has immense promise to provide an environmentally superior alternative to the harms of terrestrial livestock production (Sinke and Odegard, 2021), capture fishing and aquaculture LCAs reveal a higher benchmark for climatically sustainable protein. However, seafood LCAs have also highlighted the aforementioned threats posed to marine sustainability through the activities of these industries. Thus, exhaustively comparing the environmental efficacy of cell-based maricutlure as an alternative to conventional seafood production will require a greater assessment of the severity of these conventional seafood externalities. Value judgements must be made regarding the desirability of converting the wider impacts of conventional production into the more concentrated climatic impacts of cell-based mariculture.

LCA methodologies varied substantially between the three seafood production fields reviewed. Crucially, impact category inclusion differed greatly across studies as no impact categories except for global warming potential were included in a majority of the reviewed studies. Furthermore, variance in methodological approaches to LCA within fields limited attempts to synthesize LCA finding for use in cross-field comparison. LCA approaches for fishing and aquaculture production are still constrained by a lack of standardization, particularly in regard to analyzing fishery-specific impacts outside the usual scope of LCA. A lack of representative diversity in regard to species and geographic region also plagues capture fishing and aquaculture LCAs particularly given the lack of studies conducted in Asia. Previous reviews of capture fishing and aquaculture LCAs have extensively highlighted the shortcomings of current LCA methodologies and frameworks in documenting the full extent of environmental impacts (Avadi and Freon, 2013; Bohnes et al., 2019; Henriksson et al., 2012; Philis et al., 2019; Ruiz-Salmon et al., 2021). The recommendations these reviews have made regarding the development of a more comprehensive and standardized LCA framework should be emphasized. Meanwhile, cell-based studies were beleaguered by issues of data quality and availability that necessitated a large reliance on assumptions. Recommendations and considerations have also been posited for the use of best-practices for analyzing this developing technology (Scharf et a., 2019). The numerous issues surrounding LCA standardization, data representation, quality, and availability limit the capabilities of this research to make definitive conclusions.

Chapter 6

CONCLUSION

The development of cell-based mariculture will lead to unfamiliar environmental implications for the future production of seafood. The elimination of diffuse environmental externalities inherent in conventional approaches to seafood production suggests that cell-based seafood may eventually deliver on its promise of sustainability. However, the technology's impacts on climate change through its significant energy demands may require substantive improvements in production efficiencies and in sustainable energy generation before it can be shown to be the environmentally superior option. The trade-offs of cell-based mariculture do fit within wider environmental trends of electrification. Transforming diffuse impacts to marine resources into the singular impact of energy emissions may give cell-based mariculture's sustainability problems greater traction for improvement than currently exist within conventional means of seafood production.

Fully analyzing environmental impacts of cell-based mariculture will require development and refinement both in the technology itself and in the LCA methodologies applied to it. Moreover, there exists a considerable need for better data quality and availability of cell-based operations. Future LCAs may be necessary to hone an understanding of the impacts posed by cell-based technology. Greater improvements must also be made in LCA approaches to capture fishing and aquaculture to better reflect the extent of environmental threats posed by these operations. To develop a complete understanding of the environmental trade-offs of cell-based mariculture technology, better LCA data must be obtained from both cell-based and conventional approaches.

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