MAPPING EMERGING INDUSTRIES:

OPPORTUNITIES IN CLEAN MEAT

Liz Specht, Ph.D.
Senior Scientist, The Good Food Institute

Christie Lagally
Senior Scientist, The Good Food Institute

LAST UPDATED: JUNE 6, 2017

AN INTRODUCTION TO MIND MAPS: MAPPING EMERGING INDUSTRIES

A mind map allows the viewer to visualize critical technologies in an emerging industry and identify gaps in research and development as well as opportunities for strategic industry partnerships. This mind map illuminates opportunities for technology development in one of the most promising food tech industries: clean meat. As will be explored in more detail in a forthcoming white paper on the industry, some of these areas are best addressed by academic research, others are best suited for innovation within nimble startups, and others would be best addressed by established companies in related fields like cell therapy or industrial biotechnology.

THE CASE FOR PURSUING CLEAN MEAT RESEARCH AND DEVELOPMENT

In March 2017, the National Academy of Sciences released a report, "Preparing for Future Products of Biotechnology." The report, which was researched and written by more than a dozen top scientists and peer reviewed by an additional 17, was produced at the request of the White House with a focus on identifying the products that are likely to be produced by biotechnology in the next 10 years. In the report, clean meat is flagged as an area of high growth potential.

While the plant-based meat sector continues to make impressive strides toward parity with conventional meat in taste and texture, clean meat allows consumers to maintain their dietary preferences for animal meat while removing many of the inefficiencies and harms of current meat production. Clean meat production requires far less land and water than conventional meat, will produce exponentially less climate change, and eliminates the severe environmental repercussions of animal waste and contamination via runoff. It also requires no antibiotics, produces no bacterial contamination, and will not harm animals.

Clean meat will likely find an early market entry point as a high-value ingredient in products that are predominantly plant-based. The taste profile of meat is highly complex, comprising thousands of molecules that interact chemically in subtle, not always predictable ways with other components of food during the cooking process. As a result, the flavor of meat is not trivial to replicate or reconstitute from alternative ingredients, and adding clean meat to the mix can solve this problem without introducing the external harms of conventional animal agriculture.

Furthermore, critical technologies that are developed along the way will likely serve as lucrative intellectual property licensing opportunities for other high-value industries that rely on large-scale cell culture. Thus, investment of human and financial capital into this field is likely to pay dividends in many areas, several of which may occur on shorter timescales than the development of full-fledged, price-competitive clean meat production.

LAUNCHING AN INDUSTRY: CRITICAL AREAS OF RESEARCH AND DEVELOPMENT

The clean meat industry mind map (Figure 1) illustrates five main areas for development: cell lines, cell culture media, scaffolding and structuring, bioreactors, and supply chain and distribution. While they are displayed as discrete areas to facilitate visualization, each of these areas is closely intertwined. Thus, rapid development of the industry as a whole requires concerted communication among researchers and companies that are conducting development in different areas of this conceptual map.

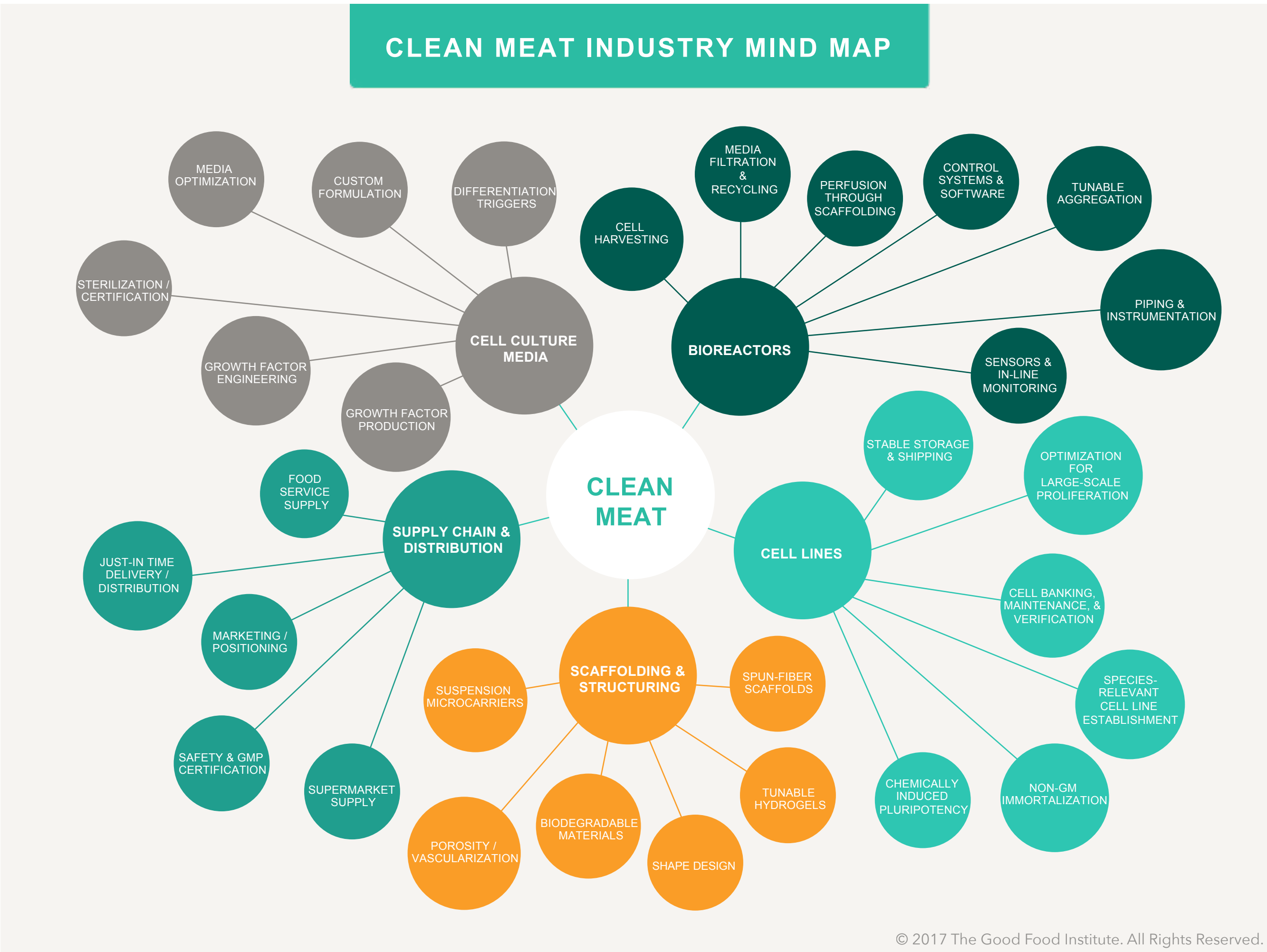

Figure 1. A conceptual mind map illustrating the primary elements for development and production of clean meat at large scale.

CELL LINES

Clean meat production begins with obtaining cell lines for the desired animal species. Generating a cell line means isolating a population of cells that is stable and immortalized. In other words, the cell line must behave in a consistent and predictable way through many generations, while maintaining an unlimited capacity to divide.

In some cases, "primary cells" directly isolated from an organism can spontaneously immortalize, meaning that they develop the ability to reproduce indefinitely without human interference. However, more stable lines may be produced through targeted modifications. Due to regulatory concerns in some countries, methods that do not rely on genetic modification may be preferred. Adult cells can also be reverted to stem cells, which are capable of proliferating indefinitely and differentiating into multiple cell types. Genetic modification has been the standard method for inducing these stem cells, but other so-called "footprint-free" methods should be explored for the clean meat field. Other modifications or adaptations – such as the ability to grow in suspension, divide more quickly, or differentiate in response to unique environmental cues – may also be introduced in the cell lines.

Once a stable, immortalized cell line exists, in theory it can be used indefinitely for production. However, even the most stable cell lines may eventually exhibit instability. Commercial cell banks store the original cell lines, provide validation services to ensure consistency, and will need to develop appropriate storage and shipping strategies for the volumes of cells needed by the clean meat field.

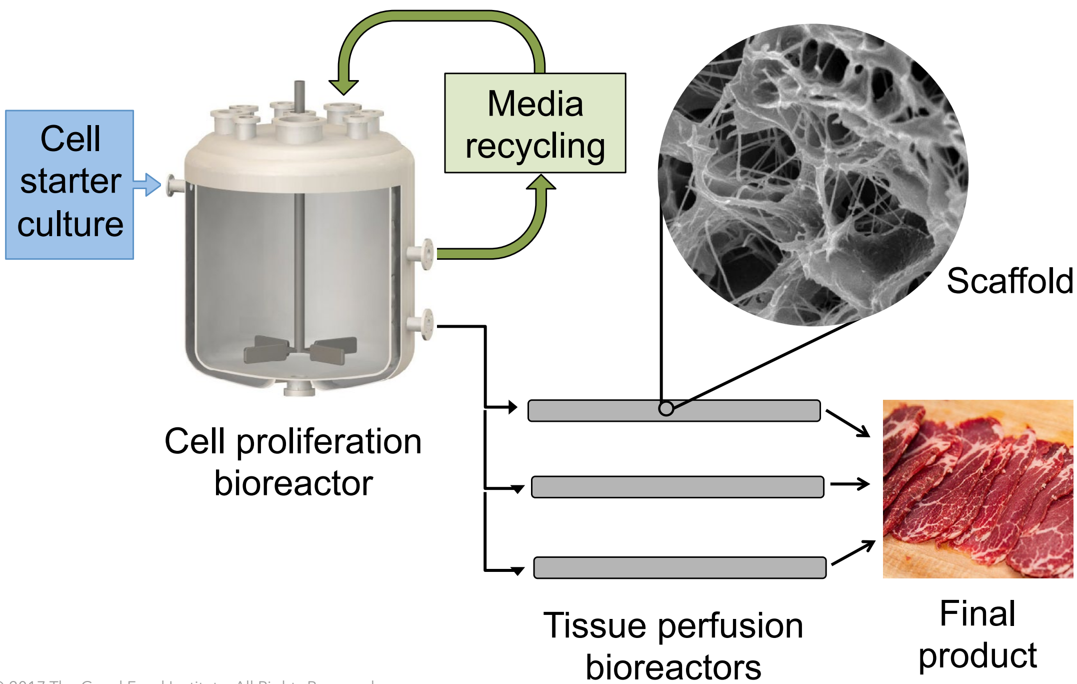

Figure 2. Schematic illustrating one conception of the process of clean meat production at scale. The first stage is proliferation of the cells, followed by a differentiation and maturation stage where cells are seeded onto scaffolds and allowed to mature into the cell types required for meat. Each of these stages presents its own design requirements for the media, scaffolding, and bioreactors.

CELL CULTURE MEDIA

Just like cells inside an organism, cells in culture require nutrients to grow. Cell culture media is a nutrient solution containing salts, pH buffers, and the building blocks of cellular structures like proteins and fats. It also contains molecules called growth factors, which are signaling molecules that direct the cells to behave in certain ways. For example, specific differentiation factors guide cells towards becoming muscle or fat or blood cells. Traditionally these factors were obtained from animal serum, but serum has already been largely phased out of cellular therapeutics and regenerative medicine. Hundreds of serum-free formulations already exist; however, they are currently too costly for commercially viable clean meat production. Customized serum-free formulations will have to be optimized for clean meat-relevant cell lines with cost as a key parameter.

Several approaches can substantially reduce the cost of media. Growth factors can be engineered for higher stability and potency, or even replaced by peptide or small molecule mimics that are far less expensive. A synthetic biology approach could be used to reengineer cellular signaling pathways to respond to benign triggers like sugars or light, thus eliminating the need for complex growth factors altogether. Finally, sourcing, sterilizing, and certification requirements may be less stringent for food applications than for biomedicine, opening another avenue for significantly reducing media costs.

SCAFFOLDING AND STRUCTURING

Scaffolds provide a support structure for cellular adherence. In the simplest case, microcarriers within a stirred bioreactor may act as scaffolds during cell proliferation. For more complex, structured products, the scaffold requirements are much more demanding and must be integrated within the final product. The material must be edible or biodegradable, as well as low-cost and made from abundant sources.

These complex products require co-culture of multiple cell types and/or differentiation while embedded within a three-dimensional scaffold. To accommodate three-dimensional growth, the scaffolds must exhibit porosity for perfusing nutrient media. Alternatively, they must support vascularization of the tissue itself, i.e., the formation of a network of vessels to allow nutrients to permeate the tissue. Several production methods, including 3D printing and spun-fiber platforms, allow fine-tuning of pore size and microstructures within the scaffold.

Scaffold materials can also assist with the cellular differentiation process. Cells differentiate in response to external molecular signals from the growth media or neighboring cells, but they are also responsive to the biomechanical properties of their environment. Materials like engineered hydrogels allow fine-tuning of parameters like stiffness, cell adherence, and even controlled release of growth factors. These cues can direct cells to differentiate into various cell types along defined regions, helping to achieve the segmented flakiness of a fish filet or the marbling found in a steak.

BIOREACTORS

Bioreactors are the machines in which every other element in clean meat production is contained: where cells proliferate, and where the transition from cells into meat occurs. As with media, clean meat bioreactors will have unique design requirements depending on the stage of production.

The proliferation bioreactors will likely be stirred tank reactors, which are already well developed for mammalian cell proliferation. Some of these systems use cells in suspension while others rely on microcarriers. Cell aggregates are also frequently used for stem cell growth, and some systems allow the formation and dissolution of such aggregates to be controlled by conditions like temperature. Regardless of the proliferation platform, the cells must be harvested efficiently for transfer into the next phase of production. For the differentiation and maturation stage, perfusion bioreactors are needed that will flow media through cell-seeded scaffolds. These bioreactors will need to be developed in close collaboration with scaffold developers.

Both proliferation and maturation bioreactor systems will need to incorporate a media recycling system to minimize inputs and waste. This system will require analytical sensors to measure concentrations of critical media components in real time and introduce fresh components as needed. Likewise, the system will need to be capable of filtering out waste products, maintaining pH and osmotic homeostasis, and maintaining real-time quality control systems. An interdisciplinary approach with intimate knowledge of cellular metabolism as well as sensors, software, piping and instrumentation, and quality control will be necessary for success on this front.

SUPPLY CHAIN AND DISTRIBUTION

As with any large industry, establishing a robust and specialized supply chain is critical for efficient product production and delivery. The most significant inputs to the system will be the primary "ingredients" of cell culture media and scaffold material. Production of both of these will likely be outsourced rather than produced in-house by clean meat companies. For each input and for the clean meat products themselves, rigorous systems must be in place to ensure safety, good manufacturing practices, and product consistency. Developing suitable transportation methods for these inputs also represents a growth area. Once the end product has been manufactured, companies will tap into larger marketing and distribution networks to make it to the hands of consumers – through foodservice and restaurants, grocers and supermarkets, or manufacturers of plant-based meats that are creating hybrid products.

TECHNOLOGICAL REQUIREMENTS FOR A VARIETY OF CLEAN MEAT PRODUCTS

Depending on the target product, clean meat producers may not require significant development in all of the above technological areas. The first products that come to market may be hybrid products wherein clean meat is included as a part of plant-based products that essentially require only cell lines, media, and proliferative bioreactors to come to fruition. The next commercial products will likely be ground meat mimics, where scaffolding can be minimal; more complex structures requiring vascularization or perfusion bioreactors are not necessarily required. Finally, more structured tissues – like those mimicking steaks or chicken breasts – will require research and development in all of the areas outlined above. Thus, a consideration of target product(s) should drive the research and development focus.

OPPORTUNITIES FOR INVOLVEMENT

Because of the novelty of this industry, opportunities for involvement exist across the entire spectrum of research, development, and commercialization.

While the majority of research and development for the explicit purpose of commercializing clean meat is occurring in start-up companies, the importance of involving established industry partners should not be underestimated – both for upstream involvement (development and production) and for downstream opportunities (such as distribution and market access). In addition, academic researchers can provide crucial technological advances for ongoing incorporation into production platforms for the next generation of clean meat production – with an eye constantly towards improving cost and efficiency.

Additionally, there is significant opportunity for researchers currently working in related fields to shift their focus towards clean meat as a novel application with immense commercial potential. Already, relevant research - both within academia and by industry leaders - has been conducted within the biomedical field -- for example, related to immortalized cell lines, xeno-free media, and co-cultures of complex tissues -- that is simply waiting to be applied to clean meat production.

As a leader in the advancement of technology and industrial development to move our food system away from conventional animal agriculture, The Good Food Institute's Science & Technology team is actively investigating and pursuing key strategies to expand the field and accelerate the commercialization of clean meat in order to create a more healthy, humane, and sustainable food supply.

See GFI.org for more information.

ABOUT THE GOOD FOOD INSTITUTE

The Good Food Institute is a 501(c)(3) nonprofit organization whose mission is to build a healthy, humane, and sustainable food system through markets and food technology. GFI is accelerating the market expansion of affordable and appetizing "clean meat" and plant-based alternatives to conventional animal products. GFI is taking ethics off the table for consumers by making the sustainable and humane choice the default choice.

ABOUT THE AUTHORS

Liz Specht, Ph.D., is a Senior Scientist at The Good Food Institute. Liz works to identify and address areas of need for plant-based and clean meat scientific innovation and works with funding agencies to prioritize research that moves this field forward. Liz holds a bachelor's degree in chemical and biomolecular engineering from Johns Hopkins University, a doctorate in biological sciences from the University of California, San Diego, and postdoctoral research experience from the University of Colorado Boulder. Liz is a Fellow with the University of Colorado at Boulder's Sustainability Innovation Lab and has a decade of academic research experience in synthetic biology, recombinant protein expression, and development of genetic engineering tools.

Christie Lagally is a Senior Scientist at the Good Food Institute. Christie works on GFI's efforts to establish technology readiness assessments for clean meat and plant-based meat and supports technology development for new research projects and product development. Christie holds bachelor's and master's degrees in mechanical engineering and has worked as a mechanical engineer on diverse projects, including space- and ground-based telescopes, natural gas engines, roller coasters, and commercial aircraft. Throughout her career, Christie has focused her areas of expertise in multidisciplinary technology development, manufacturing, automation, mathematical modeling and programming, mechanical engineering R&D, and technical and business management.

Note: This report is intended to provide a snapshot overview of the current state of technology in the clean meat industry. However, due to the nature of the industry, some technological advances may be the intellectual property of the companies that developed them and thus are not covered in this report. Furthermore, this report should be considered a living document, subject to frequent revision and updates as new information becomes available. Please refer to the first page for the date of last revision.