Good Food Institute

A summary of key findings and future directions

Anticipatory life cycle assessment and techno-economic assessment of commercial cultivated meat production

MARCH 09, 2021

Elliot Swartz, Ph.D.
Senior Scientist
The Good Food Institute

Executive summary

A life cycle assessment (LCA) and techno-economic assessment (TEA)[1] modeling a future large-scale cultivated meat (CM) production facility show that by 2030, CM could have reduced overall environmental impacts, a lower carbon footprint, and be cost-competitive with some forms of conventional meat. The LCA and TEA reports are the first of their kind to be informed by data inventories collected from active industry partners—over 15 companies involved in the CM supply chain, including five CM manufacturers contributed data and expertise. The study design, data analysis, and writing of the LCA and TEA reports was performed independently by CE Delft.

The reports point to several features as being critical to realizing the large environmental benefits and competitive costs. These include the degree of sourcing renewable energy at future facilities and further decarbonization throughout the supply chain, maintaining high-density cell cultures, efficiently using and sourcing cell culture media, and relaxing payback times for facility capital costs.

Uncertainty in the CM production process was accounted for by conservatively modeling energy use, resulting in an upper-estimate of energy demand at the facility. Additionally, conventional meat production was modeled using ambitious benchmarks that employ best practices, renewable energy at feed and farm operations, and favorable projections for further environmental impact reduction by 2030. The results from this conservative comparison indicate that the observed environmental benefits of CM in the LCA are expected to be highly robust.

While the reports aim to reflect how cultivated meat may be produced in the year 2030, data gaps persist and assumptions may change over the next decade as the nascent CM industry matures. The findings in these reports should not be interpreted as representing unchanging truths or the absolute lower boundaries for the costs and climate impacts of CM. However, the insights from these reports should be used to identify or predict with high confidence the technical and economic bottlenecks facing the CM industry.

This summary abstracts the key insights from the LCA and TEA, calling attention to areas where costs or environmental impacts can be further decreased and where gaps in knowledge still exist. Additionally, we highlight the areas of focus for technology development that are likely to be most beneficial in reducing future costs and environmental impacts. These reports collectively highlight the enormous potential for large-scale cultivated meat production as being a sustainable and affordable protein option for a growing population.

[1] Read the LCA and TEA reports from CE Delft (www.cedelft.eu). LCA (https://www.cedelft.eu/en/publications/2610/lca-of-cultivated-meat-future-projections-for-different-scenarios) and TEA (https://www.cedelft.eu/en/publications/2609/tea-of-cultivated-meat-future-projections-of-different-scenarios).

Table of contents

Study design[2]

The model construction, study design, and data analysis was performed independently by CE Delft.

Model

The model used in the life cycle assessment (LCA) and techno-economic assessment (TEA) simulates a hypothetical commercial-scale cultivated meat (CM) production facility operating in the year 2030. The facility is capable of annually producing 10 kilotons of a minced CM product.[3] To build the model, inventory data were obtained from over 15 different companies active in the CM supply chain, including five CM manufacturers. Data and bioprocess design information were independently cross-checked with multiple industry experts to assess accuracy.

A baseline scenario, based on inventory data averages (or, depending on the distribution of data, the median, geometric mean, or mode) was presented to achieve the facility's specified output. At baseline, the proliferation phase assumed that high-density cell cultures (50×10^6 cells/mL) would be grown in suspension at 37ºC in stirred-tank bioreactors, with the largest bioreactor having 10,000 L of working volume. Cells are transferred in a semi-continuous manner from the proliferation phase to the differentiation phase.[4] Differentiation occurs for 10 days in a 2,000 L working volume perfusion bioreactor, forming the CM product. Using this production method, 3,080 kg of CM is harvested every 42 days and the production line is then cleaned and sterilized. Bioprocess stages operate in parallel to meet the annual production volume of 10 kilotons. For all production phases, an antibiotic- and serum-free basal cell culture medium supplemented with three fermented recombinant proteins, two recombinant growth factors, soy hydrolysate, and select fermented and synthetic amino acids was assumed.

Life cycle assessment[5]

The LCA considered CM production from cradle to facility gate, encompassing all inputs and outputs upstream of the product leaving the facility. Comparisons were made between 1 kg of CM,[6]

---

[2] This report assumes the reader is already familiar with cultivated meat technology. For more information, visit (https://gfi.org/science/the-science-of-cultivated-meat/).
[3] Note that the terminology cultivated meat includes seafood and organ meats (e.g., foie gras). Results from the LCA imply that cultivated seafood may require less energy to produce, as these cells can be cultivated at lower temperatures. Additional analyses are needed to confirm this.
[4] Refer to Figure 5 of the LCA. The semi-continuous process assumes three independent harvests prior to cleaning and sterilization. The first two harvests are 50% of cells and the final harvest is 100% of cells.
[5](https://www.cedelft.eu/en/publications/2610/lca-of-cultivated-meat-future-projections-for-different-scenarios).
[6] 0.1 kg of a plant-based scaffold was accounted for in environmental impact calculations, but was not counted as mass for the functional unit. This avoids underestimating CM's environmental impact due to low-impact plant-based materials skewing the final results.

conventional meat (beef, dairy beef, pork, chicken), and plant-based products (tofu, wheat-based meatless products). Two energy mixes were modeled for CM production: a conventional energy mix based on stated policies for 2030 and a sustainable energy mix produced with 50% solar, 50% on-shore wind, and heating derived from geothermal heat. Environmental impacts were assessed using the ReCiPe Endpoint and Midpoint methods, which results in an environmental single score (summarized from 18 impact categories). Impacts for the carbon footprint (in CO_2-equivalents), land use, water use, and fine particulate matter formation were also quantified.

For conventional meat production, an intensive, West-European system that is significantly below global averages for carbon footprint was assumed.[7] To represent ambitious improvements in environmental impacts for conventional meat production by 2030, various assumptions were made: sustainable energy would be deployed at farm and feed production facilities, there would be reduced ammonia emissions through increased outdoor grazing, reduced methane emissions obtained through feed additives, and no land-use change associated with soy used in feed. **These assumptions reduce the total environmental impacts (ReCiPe single score) and carbon footprint of beef by 6% and 15%, pork by 11% and 26%, and chicken by 25% and 53%, respectively.** Thus, the LCA sets an ambitious benchmark — significantly below global averages[8] — for comparing the environmental impacts of conventional meat production to CM.

Techno-economic analysis[9]

The TEA considered the capital expenditures (equipment and installation costs) and operating costs (electricity, heat, water, labor, media and other inputs) that contribute to the cost of goods sold (COGS) for 1 kg of CM produced in the model facility. All equipment in the facility was assumed to be food grade rather than pharmaceutical grade, and process costs were benchmarked to the food sector. Cost estimates were assumed to be at the front-end-loading 1 (FEL-1) or conceptual stage of facility engineering and design, which implies uncertainty ranges from -20% to +40% (with a higher uncertainty bandwidth given for perfusion bioreactors). A conventional energy mix was modeled, using publicly available data for anticipated future costs (i.e., the global average electricity mix in 2030).

[7] Poore and Nemecek, 2018. See page 28 of the LCA report for further details.
[8] See Figures 1 and 3 of the LCA report.
[9](https://www.cedelft.eu/en/publications/2609/tea-of-cultivated-meat-future-projections-of-different-scenarios).

Scenario Analyses

Scenario analysis — LCA

Different manufacturers will ultimately create different bioprocesses that vary from the baseline scenario presented in the LCA. Scenario analysis was used to identify parameters where variation could result in large changes in environmental impact outcomes. This exercise allows manufacturers to focus on optimizing these parameters to limit their environmental footprint.

Upper and lower bounds in four key parameters were set. These boundaries capture a realistic range anticipated to be available to the majority of manufacturers:[10]

1. Production run time (baseline = 42 days, range = 32 days to 52 days total run time per batch)
2. Cell density (baseline = 50×10^6 cells/mL; range = 5×10^6 to 2×10^8 cells/mL)
3. Cell volume (baseline = 3500 μm^3; range = 500 to 5000 μm^3)
4. Medium efficiency, defined by the medium composition and quantity used per kg of cultivated meat (baseline = 13 L per kg of meat; range = 8 L to 42 L per kg)

Scenario analysis — TEA

Scenario analysis was similarly used to identify the most sensitive cost factors, allowing manufacturers to gain insight into the factors that significantly contribute to cost. Additionally, the question, "what set of factors will enable CM to compete on COGS with conventional meat?" was asked. Thus, the TEA modeled scenarios for relaxed payback time criteria and large but realistic future cost reductions in key cost drivers such as growth factors, recombinant proteins, and total medium inputs. In the TEA, the following scenarios compound to obtain the COGS scenarios modeled:

1. Medium costs (baseline = geometric mean of obtained data and ingredient spot prices; range = low ingredient spot prices to high ingredient spot prices listed in the report)
2. Medium efficiency, defined by the medium composition and quantity used per kg of cultivated meat (baseline = 13 L per kg of meat; range = 8 L to 42 L per kg)
3. Decreased costs of 1000X from low spot price for growth factors
4. Decreased usage of recombinant proteins by a factor of 5X and decreased costs of 100X from spot price for recombinant proteins
5. Payback time criteria ('commercial' investment criteria of 4 years, middle criteria of 8 and 16 years, and 'social' criteria of 30 years)

[10] See Table 7 in the LCA report for a full breakdown of scenario analysis findings.

In addition to these scenarios, the best-case scenarios from the LCA for cell density (2×10^8 cells/mL), cell volume (5000 μm^3), and production run time (32 days) were compounded into the model to obtain a best-case COGS scenario.

Key findings

Life cycle assessment

The LCA builds on a growing body of findings in the scientific literature[11] that show CM holds immense potential to reduce the overall environmental impacts of meat production. The LCA finds that **the environmental impacts of CM are driven primarily by the amount and sourcing of electricity used at the facility, how the inputs in cell culture medium are sourced or produced, and how efficiently the medium is used.** The key takeaways from the LCA are listed below and summarized in Table 1, with interpretation discussed in Future Directions:

1. **Even when an extremely optimistic projection featuring reduced environmental impacts of conventional animal agriculture was compared with a high, conservative estimate for energy demand for CM production, CM outperformed all forms of conventional meat production in environmental impact readouts when sustainable energy is used (Table 1).** If CM manufacturers source 30% of their energy through renewables, then the carbon footprint of CM significantly outperforms conventional beef production and becomes competitive with the global averages of conventional chicken and pork production. If CM manufacturers switch entirely to renewable energy, then CM will have fewer overall environmental impacts than all forms of conventional meat production. Importantly, sustainable energy use in the LCA is only considered for the production of CM and the cell culture media. A global transition to sustainable energy will further lower CM's environmental impacts through decarbonization elsewhere in upstream supply chains (e.g., the manufacturing of steel bioreactors).

[11] See Table 8 in the LCA report and an LCA gap analysis for a more detailed summary of previously published reports (Sharf, 2019). (https://www.gfi.org/images/uploads/2020/01/Cultivated-Meat-LCA-Report-2019-0709.pdf)

Eating this form of meat	instead of this conventional meat[12]	reduces this environmental impact category by approximately this much			
		Particulate Matter Formation[13]	Global Warming[14]	Human Toxicity[15]	Land Use
Cultivated meat (sustainable energy)	Beef (cattle)	93%	92%	92%	95%
	Beef (dairy)	85%	85%	89%	81%
	Pork	49%	52%	47%	72%
	Chicken	29%	17%	-2%	63%
Cultivated meat (conventional energy)	Beef (cattle)	90%	55%	92%	94%
	Beef (dairy)	79%	22%	89%	79%
	Pork	29%	-258%	50%	70%
	Chicken	1%	-445%	4%	60%

Table 1. Reproduced from Table 5 in the LCA report. Numbers represent the percentage change from the cultivated meat sustainable energy scenario. The ReCiPe single score for environmental impacts is driven by Particulate Matter Formation (47% of score), Global Warming (33% of score), Human Toxicity (10% of score), and Land Use (6% of score), with other categories making up the remaining 4%. For water use, see below.[16]

2. **CM outperforms all conventional meat production in resource utilization, expressed as the feed conversion ratio.** Basic thermodynamics predicts that CM would use resources more efficiently than conventional animal rearing, as those resources are spent on growing only the cells that make up the meat product rather than maintaining the day-to-day activities of an

[12] Conventional meat production modeled in the LCA has reduced environmental impacts compared to global averages. See the Study Design on page 5 for further details.
[13] Particulate matter formation refers to the mixture of solid particles and liquid droplets found in the air. It is quantified in terms of kg $PM_{2.5}$-eq and can be thought of more simply as air pollution. For animal agriculture, particulate matter formation is driven primarily by ammonia from manure and fertilizer use. For cultivated meat, it is driven by the creation of sulfur dioxide and other fine particulates from electricity generation, raw material mining, and feedstock processing upstream in the supply chain. Refer to Figure 13 of the LCA report for further details.
[14] Measured in kg CO_2-eq. For comparison to conventional beef production, cultivated meat's global warming benefits are best viewed as short-term, as beef's impacts are driven primarily by methane.
[15] Human toxicity is a metric that expresses the potential harm of a unit of chemical released into the environment. It is quantified in terms of kg 1,4DCB-eq (DCB being dichlorobenzene). For animal agriculture, it is driven primarily by manufacturing and application of fertilizers and pesticides. For cultivated meat, human toxicity is driven by mining and raw material processing for electricity production and infrastructure, as well as fertilizer and pesticide use for raw materials (i.e., soy, corn) used in the cell culture medium. To learn more about human toxicity potential, see (https://core.ac.uk/download/pdf/52101237.pdf).
[16] Blue water (found in surface and groundwater reservoirs) use was quantified. When using sustainable energy, CM uses 51 to 78% less blue water than conventional beef production, 22% more than chicken production, and 40% more than pork production. Blue water use for CM production using sustainable energy is 33% higher than conventional energy scenarios, due to the production of solar cells upstream in the supply chain. See Figure 15 of the LCA report for further details.

entire animal's body. The LCA data support this prediction (Table 2), with CM being 3.5x more efficient than conventional chicken at converting feed into meat. Increased resource efficiency translates to decreased demand for feed crops, which in turn contributes to the observed reductions in land use and water use, along with reductions in inputs such as pesticides and fertilizers.

Meat type	Feed conversion ratio (kg in per kg out)
Cultivated meat	0.8*
Beef (beef cattle)	5.7**
Beef (dairy cattle)	12.7**
Pork	4.6
Chicken	2.8

Table 2. Reproduced from Table 6 in the LCA report. *The feed conversion ratio is < 1 because of the difference in water content between inputs and outputs. **Does not include human inedible grasses in the calculation.

3. **A reduction in or elimination of active cooling can significantly further reduce the environmental impacts of CM.** Estimated energy use in the LCA is higher than some previous studies[17] due to the assumed use of active cooling, which can mitigate the metabolic heat buildup and heat inhomogeneity caused by maintaining dense cell cultures in large volume bioreactors. **The LCA shows that ~75% of the carbon footprint of CM production is driven by active cooling of the bioreactors during the large-scale proliferation stage**. The demand for cooling is difficult to predict, as it is dependent on variables such as bioreactor size, geometry, cell density, and oxygen uptake rate. Using active cooling accounts for uncertainty in these variables and represents a very conservatively high estimate for cooling demand and, in turn, energy utilization.[18] Alternatives to active cooling are discussed in Future directions.

4. **Fermentation processes upstream in the supply chain drive environmental impacts of the cell culture medium.** In sustainable energy scenarios, the medium contributes ~40% of the total environmental impact, with the majority of the impact attributed to recombinant proteins, growth factors, and some amino acids produced via fermentation. Scenario analysis identified the efficiency of medium use as a dominant driver of this environmental impact. Inefficient medium use requires higher amounts of fermented ingredients, resulting in ~40% higher

[17] Mattick, 2015.
[18] Other independent analyses imply that cooling would not be necessary for the scales modeled in this study (Humbird, 2020).

environmental impacts, whereas very efficient medium use can decrease environmental impacts from baseline by ~12 to 21%.

5. **Lower cell densities and cell volumes are secondary drivers of environmental impact. Variability in production timelines has minimal effects on environmental impacts.** In the scenarios analyzed, low cell densities and small cell volumes (at a fixed density) independently result in ~30% higher environmental impacts from baseline. Environmental impacts are increased because more bioreactors are needed to produce the same amount of CM, resulting in more energy inputs and water use for cleaning. Production timelines result in small changes (~5% or less) in environmental impacts because only small changes in the number of bioreactors are needed and nearly the same amount of medium is used. The complex relationships between achievable cell densities, cell volume, viscosity, and oxygen utilization in stirred-tank bioreactors were not explored in detail in these scenario analyses.[19]

Techno-economic analysis

The TEA aligns with previous studies[20] in identifying recombinant proteins and growth factors in the cell culture medium as the dominant cost drivers. Additionally, CM manufacturers must push the boundaries of what we know to be currently achievable for animal cell cultures in order to compete on COGS with conventional meat. The key takeaways from the TEA are below, with their interpretation discussed in Future Directions.

1. **CM can compete with some conventional meats on costs, with a COGS of $5.66 per kg ($2.57 per pound) in the best-case scenarios analyzed in this study.** Achieving costs below $7 per kg will require a combination of high density cell cultures, efficient use of food-grade media, food-grade equipment in facilities, dramatic but attainable cost reductions in recombinant protein and growth factor production, and relaxed payback time criteria for capital expenditures. Other scenarios or model designs not analyzed may further increase or decrease costs, and accordingly, the model presented here should not be interpreted as a lower bound for CM COGS.

2. **Cost reductions in growth factors and recombinant proteins (particularly albumin) hold the largest opportunity to reduce costs.** The TEA finds that the cell culture medium accounts for ~99% of baseline production costs, with recombinant proteins and growth factors accounting for an overwhelming ~99% of those medium costs. The TEA found that albumin, the most abundant protein in animal serum, contributed 80-95% of the total recombinant protein costs

[19] See Humbird, 2020.
[20] Risner, 2020; Humbird, 2020; Specht, 2019.

due to its high concentrations in the medium compared to other proteins. Under price reduction scenarios for recombinant proteins and growth factors, the medium no longer becomes the main driver of costs.

Importantly, the modeled price reductions of 1000X for growth factors and 100X for recombinant proteins may seem excessive but are actually conservative. These price reductions bring the costs to approximately ~$3M per kg of growth factors and $1000 per kg of recombinant proteins. It is well-documented that industrial proteins produced at scale often have prices in the tens of dollars per kg.[21] Thus, **availability of price points for recombinant proteins and growth factors that are an additional 100X to 100,000X from the price modifications in the TEA could reasonably be expected for CM manufacturers.** Further areas for price reduction are explored in Future directions.

3. **Relaxed payback time criteria are critical to obtaining competitive COGS.** Adopting a payback schedule over the lifetime of the facility (~30 years) as opposed to shorter payback times (~4 years) decreases COGS from ~$17.50 per kg to ~$7.75 per kg. Although this is not typical, it is reasonable to assume payback schedules may be relaxed due to governments carrying some of the investment burden, production learning curves that reduce the perceived risk for investors, and social impact motivations that increase tolerance of longer investment time horizons. Additionally, the payback time criterion is non-linear, as a payback time of 8 and 16 years results in a COGS of ~$12 and $9, respectively. This may provide greater flexibility to investors and manufacturers. A full set of recommendations for governments and other stakeholders are explored in Future Directions and in our policy-focused summary.[22]

4. **Commercial CM production will require large sums of capital investment to build new infrastructure.** The CM facility modeled in the TEA has expected capital costs of ~$450M USD (-20% to +40%), with ~57% of capital costs due to hundreds of large-volume perfusion bioreactors being required (Table 3). The model facility is larger than any current animal cell culture facility used in biopharma on a volumetric basis. Meeting just 0.3% of global meat production volume will require 100 similarly-sized facilities. **This underscores the enormous market opportunity for the development and manufacturing of more affordable, food-grade, fit-for-purpose CM bioreactors.**

[21] Puetz and Wurm, 2019.

[22] See (https://gfi.org/wp-content/uploads/2021/03/cultured-meat-LCA-TEA-policy.pdf).

Equipment type	Number of units
2.5 kL Perfusion reactors (2 kL working volume)	430
12.5 kL Stirred-tank reactors (10 kL working volume)	130
60 L Stirred-tank reactors (50 L working volume)	107
60 kL Media storage and mixing tanks	15
2.5 kL Perfusion reactors (2 kL working volume)	430

Table 3. Reproduced from Table 2 in the TEA report.

Future directions

Recommendations

The findings outlined above represent those from a singular model with its own set of assumptions. **We actively encourage CM companies, academics, and other experts to engage in the creation of new models and iterations on existing models to best inform the industry as it develops.** Updated models can be improved with the following recommendations from the key findings and insights gleaned from the LCA and TEA.

1. **The creation of hybrid products, not analyzed in these studies, are expected to make up the bulk of first-generation CM products. Hybrid products are hypothesized to have considerably lower COGS and exhibit further reduction in environmental impact relative to products composed entirely of cultivated cells. Additional studies are recommended to investigate the costs and environmental impacts of hybrid CM products.** In the LCA and TEA, 1 kg of a minced, 100% CM product was used as the functional unit, as this allows for drawing the best comparisons to conventional meats. However, many CM manufacturers are pursuing the creation of hybrid or blended products where the product contains a percentage of animal cells produced by CM methods and mixed with plant proteins, plant fats, or other materials (e.g., fermented proteins, fermented biomass, or conventional animal meat). CM products that debut over the next five years are likely to be skewed toward hybrids. The first approved CM product in Singapore is said to be composed of 70% animal cells produced via CM,[23] but a range of percentages between 1-100% CM could be expected.

[23] Dolgin, 2020. (https://www.nature.com/articles/d41586-020-03448-1).

It is well documented in this LCA and elsewhere that high-protein plant-based foods (e.g., tofu) and plant-based meats have significantly reduced overall environmental impacts compared to conventional meat.[24] Hybrid CM products with similarly-produced plant proteins or fats should be expected to decrease the product's environmental impacts. Public techno-economic assessments of plant-based meats are not available but the overall low resource requirements for plant growth and minimal intensive processing compared to CM can similarly be expected to decrease overall costs.[25] Independent studies and/or scenario analyses evaluating the environmental impacts and costs of hybrid CM products should be pursued. Additionally, LCA and TEA studies specific to cultivated fat used as an ingredient in hybrid products should be pursued.

2. **Facility location and design:**
    a. **CM manufacturers and co-manufacturers can strategically locate future facilities to reduce their environmental impacts and/or costs.**
        i. A global transition to renewable energy is expected to accelerate in the coming years and decades, ushering in a growing opportunity for CM manufacturers to locate their facilities in regions where renewable energy is abundant or can be reliably sourced. This will allow manufacturers to realize large reductions in their carbon footprint.
        ii. Renewable energy, especially solar and wind, is becoming increasingly more affordable and have begun to undercut the prices of fossil fuels in some regions.[26] The TEA shows that in the best-case scenario analyzed, electricity becomes the dominant cost driver, making up ~35% of the COGS. Facilities located in regions with access to purchasing low-cost solar, wind, hydroelectric, or geothermal energy can thus cut costs while reducing environmental impact. CM manufacturers may also opt to generate their own electricity (e.g., via installation of solar panels).
        iii. The LCA shows that with conservatively high energy use estimations, ~75% of the CM carbon footprint is driven by active cooling. One way to offset this active cooling demand, if it is needed, is by switching to passive cooling, whereby the heat produced via warming of the media and cellular metabolism is rejected through mechanisms like heat exchangers or cooling towers exposed to outside air. Colder air can reject heat more efficiently such that locating a facility in a colder climate or a climate that experiences colder temperatures for part of the year can assist in passive cooling implementation. Implementations may include use of climate-cooled natural water, deep water source cooling, or the

[24] See (https://gfi.org/blog/sustainable-meat-fact-sheet/).
[25] Specht, 2019. (https://www.gfi.org/plant-based-meat-will-be-less-expensive).
[26] Roser, 2020. (https://ourworldindata.org/cheap-renewables-growth).

addition of glycol to cooling water in closed loop systems to further reject heat in passive cooling systems that are exposed to below-freezing temperatures. Thus, a large reduction in carbon footprint can potentially be gained if CM manufacturers constructed facilities with passive cooling systems in colder climates.[27]

Cooling could also be supplied by absorption cooling technologies that rely on heat sources to provide energy for cooling processes. In these cases, heat can be derived from sustainable sources such as residual heat (sourced internally or from co-locating near an industrial site), solar heat, or geothermal.

b. **Region-specific analyses can further inform the location of facilities.**
    i. The location of a facility can have large effects on the carbon footprint and COGS but location can also influence access to labor and labor costs, the scarcity of resources, and access to material inputs and distribution channels. For example, operating a biomanufacturing facility in Bangalore, India can result in cost savings up to 75% compared to similar sites in the US or EU.[28] Likewise, if hydrolysates are used as a bulk input for amino acids (discussed further in Knowledge Gaps and Technology Development Areas), then co-location of CM facilities next to raw material processing plants could be useful. Careful selection of the thousands of new facilities that will need to be constructed for CM to become accessible to many throughout the world will greatly affect the costs, environmental impacts, and sociopolitical impacts of CM deployment. **Region-specific LCA and TEA studies can further inform CM manufacturers and co-manufacturers, input suppliers, and governments in weighing the many variables involved in facility locating.[29]**

c. **Facility blueprints and assessment of refurbishing potential.**
    i. Regulatory requirements that have bearing on facility design and construction currently remain largely undetermined for CM facilities. As regulations are elucidated, opportunities will open that can ease the time and cost burden of facility design by developing open-access blueprints.[30] Blueprints can assist in identifying facility improvements across the CM industry and allow equipment

[27] A potential tradeoff of a passive cooling system is higher water usage at the facility. To fully understand how manufacturers can balance their cooling needs, a greater understanding of the metabolism and oxygen uptake rates of cells used in CM production is needed (discussed in Knowledge Gaps and Technology Development Areas).
[28] Boyd, 2020. (https://www.genengnews.com/topics/bioprocessing/biomanufacturing-costs-in-cities-around-the-globe/)
[29] See the policy-focused summary (https://gfi.org/wp-content/uploads/2021/03/cultured-meat-LCA-TEA-policy.pdf).
[30] Read more in the GFI Solutions Database (https://gfi.org/solutions/developing-open-access-model-production-facility-blueprints/).

manufacturers and engineering firms to become familiarized with any unique requirements. Understanding the facility design will also permit a thorough assessment of refurbishing potential of existing food processing, biologics, and chemicals manufacturing facilities, which may be attractive due to limitations in the installation rate of new infrastructure.

3. **A menu of financing strategies will be needed for CM deployment at all scales.** In related industries such as fermentation, little revenue is generated from pilot to demonstration scale. Profit is typically not seen until the successful operation of the first commercial-scale facility, where economies of scale can be realized. Each new step on the scale-up ladder from pilot to demonstration to commercial may command an increase of ~10X in capital costs, with risk determined by the scaling factor of volumetric capacity. For instance, debt financiers will desire a lower risk profile, with a scaling factor near 10:1, whereas equity can be used for higher risk profiles with scaling factors beyond 50:1. Risk can also be mitigated by scale-out of mid-sized facilities. A similar path may be expected for CM, where equity financing may be abundant in the short term with more debt financing being available as confidence in the industry matures.[31] As CM's economic viability is proven out and the industry is further de-risked, debt financing will likely serve as the primary vehicle for scaling and growth.

   More mature segments of the alternative protein industry are beginning to see this play out. The appeal of the rapidly expanding plant-based meat industry has begun to incentivize governments to provide federal debt financing for new infrastructure that boosts their local economies, helps meet sustainability goals, and can increase traceability of ingredients or products, which is increasingly being demanded by consumers. For instance, Canada's climate is ideal for growing legumes such as peas that are heavily used in plant-based meat production. The government has stepped in to finance new facilities[32] and provide funding for R&D and other commercial activities related to the growth and processing of legumes and other crops.[33] As the CM industry matures, it should encourage governments to step up to provide similar support.

   In the near term, private sector and sovereign green bonds may pose one solution to the challenges inherent in securing facility financing for a high-risk, as-yet unproven, sustainable technology like CM. The issuance of green bonds places the venture's focus on sustainability at

[31] BlueNalu, a US-based cultivated seafood company, recently raised $60M in a convertible note financing round, which may signal a "middle ground" stroke of confidence between fully loaned debt and equity. (https://www.bluenalu.com/bluenalu-secures-60-million-in-convertible-note-financing).
[32] The government of Canada has recently provided financing of $100M for a new pea and canola protein processing facility. (https://www.newswire.ca/news-releases/boosting-canada-s-reputation-as-a-global-leader-in-plant-proteins-865970517.html).
[33] Canada's Protein Industries Supercluster. (https://www.ic.gc.ca/eic/site/093.nsf/eng/00012.html).

the forefront and may significantly relax facility payback time expectations, which the TEA shows can have a significant effect on COGS. Small CM startups may also take a “capital-light” scale-up approach and partner with large multinationals for the manufacture and distribution of CM. This approach allows the startup to effectively outsource scale-up risk to a large entity with a steady, diversified income stream and proven bioprocess or food production infrastructure and expertise. CM companies are beginning to pursue this strategy,[34] and it has become increasingly common in the fermentation segment of the alternative protein industry.

Knowledge gaps and technology development areas of focus[35]

The LCA and TEA highlight important data and knowledge gaps that currently exist for CM production. Many of these gaps lie in the traits of the specific cells being used for production, which have often been minimally studied in other contexts, and how those traits can be leveraged for improved productivity. The continued creation of cell line repositories and open-access cell characterization data will be crucial for optimization of CM production.[36] Additionally, knowledge gaps and whitespace opportunities exist for the bioreactor equipment that will need to be tailor-made for CM production. Improvements in or implementation of the topics discussed below would be valuable to include in future LCA and TEA models.

1. **Opportunities for decreasing the environmental footprint and costs of recombinant protein and growth factor production are abundant.[37]** In the LCA, it is assumed that recombinant proteins, growth factors, and supplemented amino acids are primarily supplied via microbial fermentation, and these inputs account for the majority of the environmental impact of the cell culture medium. Additionally, these ingredients as they are produced today account for 99% of costs. Additional ways to decrease the costs and environmental impacts for these ingredients should be investigated:
    a. Recombinant proteins or growth factors can be produced in less resource-intensive hosts such as plants or platforms such as cell-free protein synthesis systems. Comparative LCAs across different recombinant protein production hosts and platforms would be informative for the CM industry.
    b. Required amounts of recombinant proteins and growth factors can be reduced in numerous ways, including but not limited to engineering more potent or thermostable

[34] Aleph Farms, an Israel-based CM company, signed a memorandum of understanding outlining a partnership with Mitsubishi to bring its CM products into the Japanese market. (https://www.prnewswire.com/news-releases/aleph-farms-and-mitsubishi-bring-cultivated-meat-to-japan-301200863.html).
[35] Explore GFI’s Solutions Database for addressing challenges in cultivated meat. (https://gfi.org/alternative-protein-solutions/).
[36] Contribute cell lines for the cultivated meat community. (https://gfi.org/resource/expanding-access-to-cell-lines/).
[37] A forthcoming analysis using industry data will examine more deeply the cost reduction possibilities for recombinant proteins and growth factors used in CM production.

variants, developing encapsulated or slow-release systems, using conditioned medium from other animal cell lines, relying on high-density cell cultures to become self-sustaining, or by discovering biofunctional equivalents in plants or other organisms. These methods collectively could allow manufacturers to use lower amounts of recombinant growth factors and, in turn, decrease costs and environmental impacts.

c. Recycling of specific medium components could reduce the environmental burden and costs of CM; however, to date, no such sophisticated or commercialized medium recycling systems exist. Dialysis serves as one example of how medium recycling for proteins may be implemented,[38] which may be especially important for albumin — a primary driver of medium costs in the TEA. Future models may incorporate real or hypothetical medium recycling scenarios to better understand its utility in CM production as well as understanding the potential environmental and economic trade-offs if recycling operations are energy-intensive.
d. Serum- and albumin-free medium formulations are commonplace for the culturing of pluripotent stem cells, which increases confidence that albumin may be able to be eliminated entirely from use in CM manufacturing. Research into the mechanistic underpinnings of successful albumin-free media is suggested.

2. **Data gaps exist for cellular metabolism and oxygen uptake rates (OUR) for the species and cell types used in CM.** A different CM TEA[39] modeled the relationships between OUR, metabolite accumulation, and maximum cell densities given a hypothetical cellular metabolism, bioreactor format, and volume. The study concludes that limitations in animal cell metabolism and bioreactor operational constraints collectively result in insufficient productivity that will hinder CM costs from being competitive. In the TEA presented here, which we believe to more accurately represent future CM manufacturing, the use of plant protein hydrolysates in the media, reduced recombinant protein costs, food-grade production equipment and facilities, deployment of different media sterilization procedures, and relaxed payback time criteria for capital costs sufficiently offset the COGS imposed by these limitations.

   Despite these differences, the LCA and TEA presented here similarly finds that unknowns in cellular metabolism have dramatic implications on the manufacturing process as well as the environmental footprint, resulting in conservative assumptions for metabolic heat production, which in turn influence heating and/or cooling demand at the facility. Each model contains its own set of assumptions but their conclusions collectively point toward a need for a greater understanding of cellular metabolism and its role in CM production.

[38] Nath, 2017.
[39] Humbird, 2020.

To help resolve remaining questions, researchers in academia and industry may collect data and develop technologies for the following:

a. **Measurement of oxygen uptake rates for cells used in CM production.** The OUR of specific cell lines is known to vary within and between species[40] and can fluctuate depending on many variables. Researchers may use existing methods or develop new tools and methods to measure the dynamic OUR for cell types and species subjected to varying growth conditions and bioreactor environments. These data can inform overall bioprocess design and be incorporated in future LCA and TEA models.
b. **Improvements in oxygen transfer.** In animal cell culture, sufficient oxygen transfer is often a limiting factor. Improvements in oxygen transfer may be made by further research and development into, for example, novel impeller designs to improve mixing[41] and oxygen carriers (e.g., recombinant heme proteins).[42]
c. **Metabolism of cells used in CM production and metabolic changes during differentiation.** Mapping the metabolism of the various cells and species used in CM production can inform media development and be used to refine future LCA and TEA models. The creation of genome-scale metabolic models and application of, for example, metabolic flux analyses and genome engineering can assist in understanding the range of metabolic profiles likely to be encountered in the CM industry. Additionally, the metabolic changes that occur from proliferation to differentiation can be incorporated into future LCA and TEA models that more closely dissect the differentiation stage of production, which has not been modeled in detail to date.
d. **Mapping hydrolysate composition to metabolic requirements.** In the LCA and TEA, media is supplemented with soy hydrolysate, which has a relatively similar amino acid profile compared to the common basal cell culture medium DMEM/F12.[43] In reality, different cell types utilize different amino acids to varying degrees and rates. For instance, glutamine is typically one of the most consumed amino acids in mammalian cell culture, but is dispensable for pluripotent stem cell culture.[44] Accordingly, to be the most cost-effective, the concentrations of amino acids in cell culture media should match the consumption rates for each specific species and cell type. Hydrolysates from a variety of different sources such as plants, fungi, or algae, or other microbes can be compared on the basis of cost, sustainability, and metabolic fit for individual CM production cell lines. Blends of suitable hydrolysates can be used to counterbalance deficiencies in amino acid composition (or vitamin and micronutrient levels) from single

[40](https://www.cytivalifesciences.com/en/us/solutions/bioprocessing/knowledge-center/7-factors-that-affect-oxygen-transfer-to-cells-in-bioreactors).
[41] (https://www.cellmotions.com/pages/technology)
[42] Le Pape, 2015.
[43] See Humbird, 2020.
[44] Vardhana, 2019.

sources. Upscaling the raw material sources of hydrolysate blends that best fit the needs of the industry and determining whether they will be required at food- or feed-grade can further reduce costs. The same raw materials may also serve as inputs across the alternative protein industry for plant-based meats, fermentation feedstocks, or scaffolding for CM.

e. **Media recycling and sidestream valorization.**[45] As mentioned above, media recycling of recombinant proteins can help in reducing the cost and environmental impact of CM production, but it may also be used to mitigate the accumulation of toxic metabolic byproducts such as ammonia and lactic acid. As commercially important biomolecules, ammonia and lactic acid can be incorporated or converted into a range of downstream products (e.g., fertilizers, bioplastics, feedstock ingredients). In theory, ammonia and lactic acid can be separated and purified from a liquid media, but the ends would have to justify the means. Cost-benefit models for ammonia and lactic acid separation and purification should be applied to CM production models using input data gathered in (a) - (c) above to determine the potential utility of their application.[46] If ammonia and lactate can be recovered and used in, for example, upstream feedstocks, it could replace virgin production of those components and the environmental impacts of those components could be subtracted from CM production.

   Another abundant sidestream to investigate could be CO_2 “exhaled” from cells during growth. In the US, the ethanol industry supplies approximately 45% of domestic CO_2 used in, for example, foods, beverages, and dry ice. Additionally, advances in carbon capture and sequestration technology are increasingly becoming implemented at large-scale fermentation biorefineries[47] and may hold potential for similar implementation for CM production at sufficiently large scales. Thus, further investigation into using CO_2 byproducts to offset the costs or carbon footprint of CM production is warranted.

   Lastly, secreted paracrine factors including growth factors, proteins, and extracellular vesicles will be produced in large quantities during CM production. Excess secreted factors can be harvested and used as media supplements for industrial CM production, CM research in academia, or human and veterinary regenerative medicine applications.

[45] Note that conventional agriculture also produces numerous co-products (e.g., leather, gelatin, pet foods, cosmetics). Comparisons between co-products fall outside the scope of this report. Virtually every category of animal-derived co-product is currently being pursued via fermentation or methods similar to cultivated meat production. Future LCA and TEA models may incorporate comparisons between co-product categories as more data becomes available.
[46] Note that other options for mitigating metabolite buildup exist, such as perfusion, adaptation, or genetic engineering.
[47] Sanchez, 2018.

3. **Improved bioreactor designs and operation.**
    a. **Perfusion bioreactors.** In perfusion bioreactors, cells are retained via a substrate or collection method while media passes through the vessel at a fixed rate. Perfusion bioreactors are hypothesized to be critical to the differentiation phase of CM production, especially for structured products, as cell differentiation often requires a fixed substrate.[48] In the LCA and TEA, it is assumed that a 2.5 kL perfusion bioreactor can be used to differentiate cells prior to product harvesting and these bioreactors account for ~57% of the facility costs in the TEA. However, the reader should note that to our knowledge, the large-volume perfusion bioreactor systems as described in the LCA and TEA do not yet exist.

       Many types of perfusion bioreactors exist today at smaller scales but often serve purposes other than strictly accumulating cell mass (e.g., growing fixed cells while harvesting a secreted product). Future work should be focused on optimizing existing systems or developing new systems that can efficiently expand or differentiate skeletal muscle and adipose tissue or support co-cultures of multiple cell types. Conceptually, this could require embedding scaffolding structures within a bioreactor or using permeable biomaterials to house encapsulated cells in spheres, sheets, or tubes. Further development of fit-for-purpose perfusion bioreactors for CM production offers a large whitespace opportunity for new companies.
    b. **Animal cell bioreactors for food production.** To date, the processes and equipment for biomanufacturing of animal cells have been developed for the biopharma or biomedical sectors. Accordingly, equipment and facilities must adhere to strict regulatory requirements and certifications used in those sectors. The biomanufacturing of animal cells in a food facility presents a unique regulatory challenge. Changes to configurations for contamination mitigation and sterilization processes may be unavoidable, but others may change in accordance with to-be-determined requirements being currently weighed by global teams of regulators.

       In the TEA, facility costs and equipment were benchmarked to bioprocesses in the food sector to accommodate these anticipated changes. These result in lower costs when compared to biopharma benchmarks. Designers and suppliers of the large numbers of bioreactors that will feed into CM production must be aware of potential changes in manufacturing requirements to accommodate the food-grade nature of the process.

[48] Some degree of differentiation is possible in spheroids or on microcarriers, but this is likely insufficient to meet the requirements of whole-cut muscle products.

Consideration for bioreactor manufacturing should thus involve food-grade processes and food-safe contact materials throughout.[49]

c. **Continuous processing.** Continuous processing permits the production of cells without interruption. The implementation of continuous processing can lead to increases in production uptime, labor efficiency, and resource savings due to decreases in cleaning and sterilization frequency. Continuous processing of animal cells poses a greater challenge in maintaining aseptic operation, as increased uptime corresponds to an increased probability of contamination. Accordingly, greater controls may be required for continuous process designs. Continuous processing represents another broad category of whitespace opportunities in CM production.

d. **Automation.** CM manufacturers should consider early and often the implementation of automation in their facility and bioprocess designs wherever possible. Like continuous processing, automation can result in increases in production uptime, labor, and resource efficiency. Industry-wide collaborations that identify the critical process parameters best improved by automation could lead to standardization across software, sensor systems, or other hardware components that enable automation implementation.

e. **Computational modeling.** Research and development time and costs can be significantly reduced by simulating experiments as computational models. Computational modeling can be used to assist medium formulation development, bioreactor and bioprocess design, scale-up, and scaffold development. Modeling should be performed in tandem with experimentalists that can validate simulations, provide input data, and implement identified improvements. The Cultivated Meat Modeling Consortium, consisting of computer modelers and CM scientists from academia, life science companies, CM manufacturers, and nonprofits has initiated several projects applying modeling to accelerate the scale-up of CM processes.[50]

4. **Additional implications of a transition to CM.** The LCA and TEA only account for the environmental impacts from cradle to facility gate, which means that the packaging, distribution, and end-product consumption is not accounted for in the analysis. CM is hypothesized to have additional external benefits related to climate change, human health, and food security other than those discussed in the LCA and TEA reports. Future analyses may examine the add-on effects of a future where substantial market share is won by CM or other

[49] Although not modeled in the LCA and TEA, single-use bioreactor bags are becoming more commonplace in biopharma as they can decrease operational costs and feature improved sustainability metrics compared to steel stirred-tank reactors, depending on energy sourcing. See https://www.cytivalifesciences.com/en/us/solutions/bioprocessing/knowledge-center/single-use-and-sustainability. CM manufacturers may similarly pursue use of single-use technologies. Accordingly, the polymer bags should be designed with food-grade materials. Future LCA and TEA models assessing single-use technologies would be valuable.

[50] (www.thecmmc.org).

alternative proteins versus conventional counterparts. Additional analyses of value, which may also be region-specific, are listed below.

a. **Effects of decreased land use and assessing carbon opportunity costs for meat production.** It will be important to understand how the benefits of CM's decreased land requirements may be leveraged to convert existing feed crop or animal agricultural lands into production of more foods for humans, repurposed land for renewable energy production, or rewilded habitat to sequester additional carbon if dietary substitution of CM instead of conventional meats take place.[51] It would also be valuable to examine add-on effects from dietary substitution that could lead to reduced eutrophication potential, pesticide usage, and limited rates of deforestation, biodiversity, and other habitat loss.

b. **Effects of decreased microbiological counts on final products.** Due to the nature of its manufacturing process, CM is expected to have minimal bacteria present on the final product.[52] Analyses may aim to quantify the add-on climate impact effects due to these characteristics, such as reduced meat and seafood waste due to reduced bacteria-mediated spoilage and the potential to reduce the burden of cold-chain transport.

   Additionally, many of the most common causes of foodborne illness related to animal slaughter (e.g., *E. coli, Campylobacteria, Salmonella)* are not expected to be present in CM. Thus, CM should significantly reduce the incidence rates of foodborne illness caused by meat and seafood consumption.

c. **Effects of meat and seafood production without antibiotics.** Antibiotics are not anticipated to be used in CM production[53] and a switch to CM could thus save on the over 200,000 tons of annual antibiotic use expected to be attributed to animal agriculture by the year 2030.[54] The potential human health, terrestrial and marine ecotoxicity, and economic benefits are massive in light of the growing prevalence of antibiotic resistance, poor incentive environment for the discovery of new antibiotic drugs in biopharma, and poor disposal practices of hazardous antibiotic mycelial residues.[55]

d. **Mitigation of zoonotic disease and global pandemic risk.** COVID-19 has demonstrated that the human population is still vulnerable to devastating pandemics. Approximately 75% of new and emerging infectious diseases are zoonotic in origin,[56]

---

[51] For more, see (https://gfi.org/wp-content/uploads/2021/03/cultured-meat-LCA-TEA-policy.pdf).
[52] Data to support these claims are currently limited. Additional data is anticipated to become available upon the regulatory approval of additional CM products or ongoing academic research.
[53] The first approved CM product in Singapore is produced without antibiotics (https://goodmeat.co/).
[54] Van Boeckel, 2017.
[55] Chen, 2017.
[56] (https://www.who.int/neglected_diseases/diseases/zoonoses/en/).

and the vast majority of these originate in livestock or other domesticated and intensively farmed animals.[57] The consequences of a significant shift to CM production should be examined seriously as a means to mitigate the risk of zoonotic disease originating from intensively farmed animals.

These suggestions represent a non-exhaustive list of the potential add-on effects of a transition to CM. We encourage cross-disciplinary teams within governments, academia, industry, and nonprofits to explore the implications of future scenarios where CM is a mature industry with accelerating market share.

Conclusion

The future large-scale CM production facility outlined in this report is the first to combine techno-economic and life cycle assessments derived from a single model that is informed by industry data. The LCA and TEA highlight the critical technical bottlenecks and areas of focus for CM manufacturers to implement in their production processes to achieve desired economic and environmental impact outcomes, and together serve as a foundation for refined future models. The studies also highlight the need for further open-access research on the species and cell types used in CM production, development of new or improved core technologies, and global shifts in the energy sector for CM technology to deliver on these potential sustainability gains. Coordination across various stakeholder groups including interdisciplinary scientists in industry and academia, CM manufacturers, investors, nonprofits, governments, and other policymakers will be crucial to the successful future of CM and other alternative proteins.[58] The findings outlined in the LCA and TEA reports lend further confidence to CM technology that can serve as a rallying cry for these stakeholders to unite in creating a viable solutions-oriented path forward.

[57] COVID-19 is zoonotic in origin but is not directly attributable to intensively farmed animals.
[58] See the summary of recommended stakeholder actions: (https://gfi.org/wp-content/uploads/2021/03/cultured-meat-LCA-TEA-policy.pdf).

References

1. Boyd, J. H. 2020. "Biomanufacturing Costs in Cities around the Globe." June 5, 2020. https://www.genengnews.com/topics/bioprocessing/biomanufacturing-costs-in-cities-around-the-globe/.
2. Chen, Wei, Yong Geng, Jinglan Hong, Harn Wei Kua, Changqing Xu, and Nan Yu. 2017. "Life Cycle Assessment of Antibiotic Mycelial Residues Management in China." *Renewable and Sustainable Energy Reviews* 79 (November): 830–38.
3. Dolgin, Elie. 2020. "Will Cell-Based Meat Ever Be a Dinner Staple?" *Nature* 588 (7837): S64–67.
4. Humbird, David. 2020. "Scale-Up Economics for Cultured Meat: Techno-Economic Analysis and Due Diligence." https://doi.org/10.31224/osf.io/795su.
5. Le Pape, Fiona, Morgane Bossard, Delphine Dutheil, Morgane Rousselot, Valérie Polard, Claude Férec, Elisabeth Leize, Pascal Delépine, and Franck Zal. 2015. "Advancement in Recombinant Protein Production Using a Marine Oxygen Carrier to Enhance Oxygen Transfer in a CHO-S Cell Line." *Artificial Cells, Nanomedicine, and Biotechnology* 43 (3): 186–95.
6. Mattick, Carolyn S., Amy E. Landis, Braden R. Allenby, and Nicholas J. Genovese. 2015. "Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States." *Environmental Science & Technology* 49 (19): 11941–49.
7. Nath, Suman Chandra, Eiji Nagamori, Masanobu Horie, and Masahiro Kino-Oka. 2017. "Culture Medium Refinement by Dialysis for the Expansion of Human Induced Pluripotent Stem Cells in Suspension Culture." *Bioprocess and Biosystems Engineering* 40 (1): 123–31.
8. "Plant-Based Meat for a Growing World." 2019. The Good Food Institute. https://www.gfi.org/images/uploads/2019/08/GFI-Plant-Based-Meat-Fact-Sheet_Environmental-Comparison.pdf?utm_source=blog&utm_medium=website&utm_campaign=pb-meat-sustainability.pdf&gh_src=245a4c8a2.
9. Puetz, John, and Florian M. Wurm. 2019. "Recombinant Proteins for Industrial versus Pharmaceutical Purposes: A Review of Process and Pricing." *Processes* 7 (8): 476.
10. Risner, Derrick, Fangzhou Li, Jason S. Fell, Sara Pace, Justin B. Siegel, Ilias Tagkopoulos, and Edward Spang. 2020. "Techno-Economic Assessment of Animal Cell-Based Meat." https://doi.org/10.1101/2020.09.10.292144.
11. Roser, M. 2020. "Why Did Renewables Become so Cheap so Fast? And What Can We Do to Use This Global Opportunity for Green Growth?" 2020. https://ourworldindata.org/cheap-renewables-growth.
12. Sanchez, Daniel L., Nils Johnson, Sean T. McCoy, Peter A. Turner, and Katharine J. Mach. 2018. "Near-Term Deployment of Carbon Capture and Sequestration from Biorefineries in the United States." *Proceedings of the National Academy of Sciences of the United States of America* 115

(19): 4875–80.

13. Scharf, Andreas, Elke Breitmayer, and Michael Carus. 2019. “Review and Gap-Analysis of LCA-Studies of Cultured Meat.” https://www.gfi.org/images/uploads/2020/01/Cultivated-Meat-LCA-Report-2019-0709.pdf.
14. “Single-Use Technology and Sustainability: Quantifying the Environmental Impact in Biologic Manufacturing.” 2020. Cytiva. https://cdn.cytivalifesciences.com/dmm3bwsv3/AssetStream.aspx?mediaformatid=10061&destinationid=10016&assetid=16801.
15. Specht, Liz. 2018. “An Analysis of Culture Medium Costs and Production Volumes for Cell-Based Meat.” The Good Food Institute. https://www.gfi.org/files/sci-tech/clean-meat-production-volume-and-medium-cost.pdf.
16. ———. 2019. “Why Plant-Based Meat Will Ultimately Be Less Expensive Than Conventional Meat - The Good Food Institute.” June 18, 2019. https://www.gfi.org/plant-based-meat-will-be-less-expensive.
17. Van Boeckel, Thomas P., Emma E. Glennon, Dora Chen, Marius Gilbert, Timothy P. Robinson, Bryan T. Grenfell, Simon A. Levin, Sebastian Bonhoeffer, and Ramanan Laxminarayan. 2017. “Reducing Antimicrobial Use in Food Animals.” *Science* 357 (6358): 1350–52.
18. Vardhana, Santosha A., Paige K. Arnold, Bess P. Rosen, Yanyang Chen, Bryce W. Carey, Danwei Huangfu, Carlos Carmona-Fontaine, Craig B. Thompson, and Lydia W. S. Finley. 2019. “Glutamine Independence Is a Selectable Feature of Pluripotent Stem Cells.” *Nature Metabolism*, July. https://doi.org/10.1038/s42255-019-0082-3.

About the author

Elliot's work at GFI focuses on accelerating the cultivated meat industry by analyzing the intersection of diverse scientific disciplines with cultivated meat, leading key GFI-sponsored research projects in cultivated meat, and educating scientists, the public, and other industry stakeholders. Elliot holds a Ph.D. in neuroscience from UCLA where he worked with induced pluripotent stem cells to model human neuromuscular disease.

Elliot Swartz, Ph.D.
Senior Scientist, The Good Food Institute
elliots@gfi.org Elliot Swartz @elliotswartz

Acknowledgments

The Good Food Institute would like to thank the research team at CE Delft — especially Ingrid Odegard, Pelle Sinke, and Robert Vergeer for managing and assembling the LCA and TEA reports. GFI would like to thank GAIA for co-commissioning the LCA report. GFI is immensely grateful to all of the data providers and knowledge collaborators for making this work possible.

The Good Food Institute is a 501(c)(3) nonprofit organization. Our family of donors powers our progress toward a world where alternative proteins are no longer alternative.

About GFI

The Good Food Institute (GFI) is a 501(c)(3) nonprofit working internationally to make alternative proteins like plant-based and cultivated meat delicious, affordable, and accessible. GFI advances open-access research, mobilizes resources and talent, and empowers partners across the food system to create a sustainable, secure, and just protein supply.