gfi Good Food Institute

MG CONSULTING

Amino acid cost and supply chain analysis

for cultivated meat

Authors

Marie Gibbons, MS, independent cultivated meat scientist,
https://www.mariegibbonsconsulting.com

Amanda Bess, PhD,
senior analysis program manager

Elliot Swartz*, PhD,
senior principal scientist, cultivated meat

*Corresponding author: elliots@gfi.org

Suggested citation: Gibbons, M., A. Bess, and E. Swartz. Amino acid cost and supply chain analysis for cultivated meat. Washington D.C.: Good Food Institute. 2025. https://doi.org/10.62468/xcjx6040

Graphic design and copy edit: Kelli Cromsigt, Emily Hennegan, Joe Gagyi, Tara Foss

About GFI

The Good Food Institute is a nonprofit think tank working to make the global food system better for the planet, people, and animals. Alongside scientists, businesses, and policymakers, GFI's teams focus on making plant-based, fermentation-enabled, and cultivated meat delicious, affordable, and accessible. Powered by philanthropy, GFI is an international network of organizations advancing alternative proteins as an essential solution needed to meet the world's climate, global health, food security, and biodiversity goals. All of GFI's work is made possible by gifts and grants from our global community of donors. If you are interested in learning more about giving to GFI, contact philanthropy@gfi.org. To learn more, please visit www.gfi.org.

Executive summary

Unlocking a cost-effective amino acid supply is essential to scaling the cultivated meat (CM) industry. Amino acids represent a significant cost driver for CM production, due not only to the large quantities required, but also the complex supply chain needed to deliver them at the scale and suitability for food applications.

This white paper evaluates pathways to supply amino acids at the cost and volume required for a competitive cultivated meat industry. Through a first-of-its-kind analysis of future amino acid requirements, alternative sourcing strategies, and real-world price data, it equips stakeholders—from amino acid suppliers to CM producers—with the insights needed to prioritize the most impactful research and supply chain solutions as the CM industry scales.

This report demonstrates that while amino acids remain a major cost consideration, they are not an insurmountable financial barrier. With proactive production scale up, innovation in low-cost source materials, and alignment on clear regulatory requirements, the cultivated meat industry is well-positioned to unlock more affordable, scalable, and sustainable protein production.

Approach

1. Collected data and insights from structured interviews with stakeholders across the supply chain, including amino acid suppliers, cell media formulators, cultivated meat producers, and hydrolysate experts.
2. Modeled total and individual amino acid usage to produce 250 kilotonnes (kTA) of CM using commercially-relevant media formulations and estimates of amino acid requirements (200–650 g total AA/kg CM).
3. Estimated the amino acid cost contribution per liter of media and per kg of CM across two food-grade amino acid price tiers based on real-world quotes and one feed-grade price tier derived from aggregate supplier data.
4. Assessed the potential of 50 raw materials and hydrolysates to supply bulk amino acids and calculated price thresholds for hydrolysates to be competitive with amino acids derived from fermentation.

Key Findings

1

Amino acid costs are significantly lower than previously estimated

Real-world prices for food- and feed-grade amino acids are up to 10× lower than the figures used in a previous, highly-cited study (Humbird 2021). If the industry can source amino acids at lower-tier food-grade prices and achieve efficient production, amino acid cost contributions could fall below $5/kg of cultivated meat—a major improvement over previous estimates of ~$18–$19/kg, which accounted for up to half the total cost of cultivated meat production (Humbird 2021). Total amino acid cost contributions to commercially-relevant media ranged from $0.02 to $0.17/L depending on the formulation and price (**Figure 1**). This suggests total media costs under $0.20/L are achievable, aligning with recent reports from companies in the sector. These updated amino acid price estimates should now serve as the most realistic baseline for future techno-economic and media cost modeling.

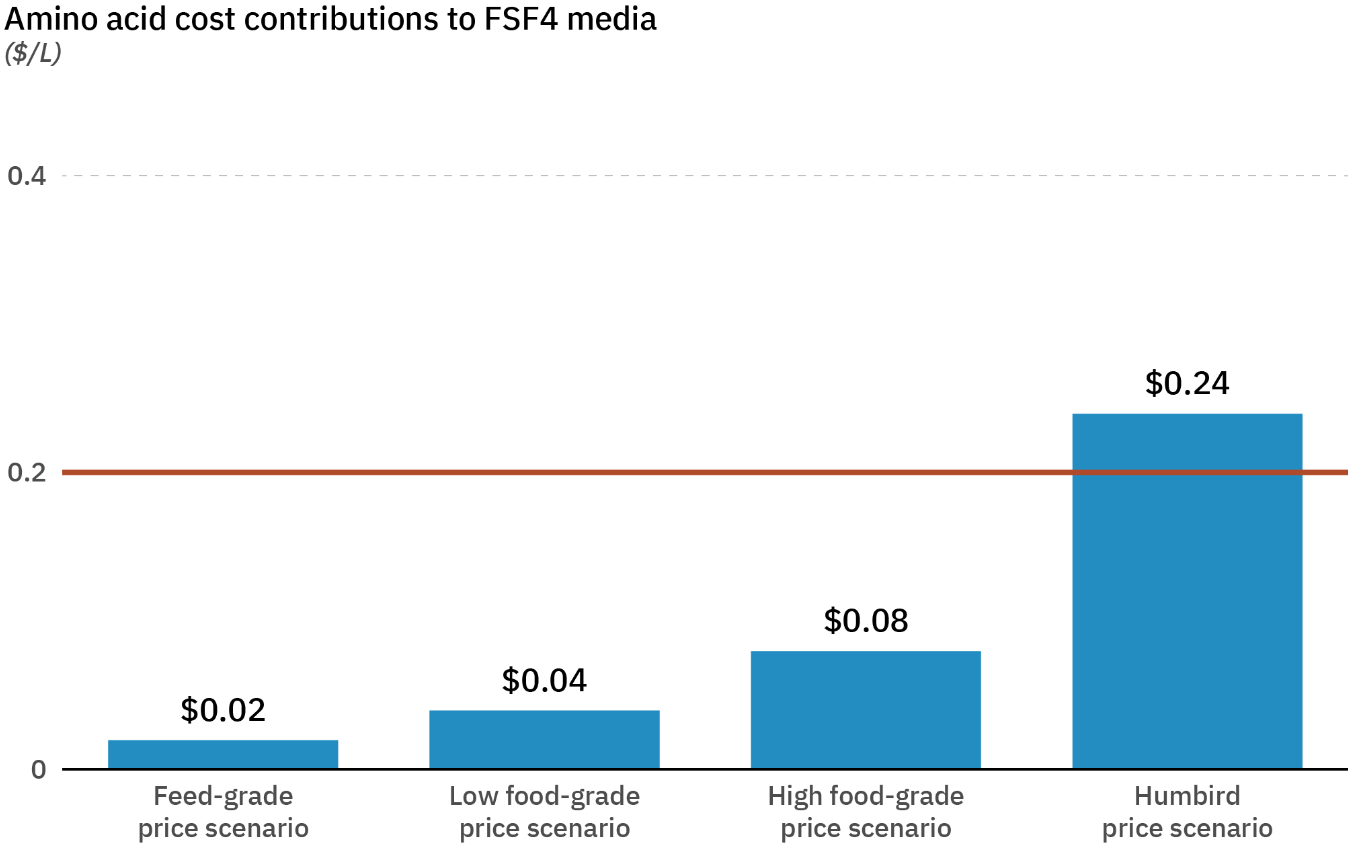


Figure 1. Total amino acid cost contributions to a commercially-relevant media formulation across four different price scenarios, with a red reference line at $0.20/L to represent recent reports from companies in the sector. Data for an additional media formulation are shown in Figure 6.

2

Projected amino acid requirements could strain global supply

Although current amino acid supply and media manufacturing capacity are adequate for today's needs, this could quickly change in the future. At a future production volume of 250 kTA of cultivated meat, which equates to less than 1% of current global meat consumption, total amino acid requirements could reach ~50–163 kTA. Arginine, glutamine, and serine are each projected to exceed 10,000 MT/year, with eight additional amino acids requiring at least 2,200 MT/year. Asparagine, glutamine, histidine, proline, serine, tyrosine, and, to a lesser extent, leucine and isoleucine, were identified as high-risk for future supply bottlenecks due to future demand potentially outstripping current production volumes.

3

Hydrolysates hold strong long-term potential despite limitations

Hydrolysates and raw materials are consistently deficient in key amino acids like glutamine, arginine, cystine, serine, and asparagine, necessitating supplementation. Additionally, a single hydrolysate is unlikely to practically supply the remaining amino acids, likely requiring blending of two or more hydrolysates. Even so, several blends of hydrolysates were able to supply up to 60% of the required amino acids in modeled scenarios. To compete with fermentation-derived amino acids, hydrolysate blends would need to cost between $1.51–$11.27/kg hydrolysate. Batch-to-batch variability, solubility issues, and limited compositional data remain barriers to widespread adoption. While there is enthusiasm for hydrolysates and current testing within R&D programs, near-term CM products are unlikely to utilize them for amino acid supplementation until these challenges are resolved.

Photo credit: Влад Варшавский / Adobe Stock

4

Six amino acids pose outsized cost and supply risks

Six amino acids—serine, glutamine, asparagine, histidine, proline, and arginine—emerged as the most problematic due to high inclusion rates, elevated prices, low global production volumes, or manufacturing complexity (**Figure 2**). Serine stood out, contributing between ~16-38% of total amino acid costs in media. Furthermore, most of these amino acids are difficult to replace with hydrolysates and are likely to remain reliant on fermentation. Strategic efforts to improve production efficiency, diversify sourcing, and reduce costs for these high-impact inputs will be critical for long-term scalability.

High-risk amino acids

	Cost driver	Potential supply bottleneck	Difficult to replace with hydrolysate
Arginine	●		●
Asparagine	●	●	●
Cyst(e)ine	○		●
Glutamine	●	●	●
Histidine	●	●	
Isoleucine		○	
Leucine		○	
Proline	●	●	
Serine	●	●	●
Tyrosine		●	

Figure 2. High-risk amino acids. Heatmap summary of key results from the analysis, which shows the overlap in amino acids that are cost drivers, in limited supply, and difficult to replace with hydrolysates. Lighter shades indicate lower risk.

Calls to action

Cultivated meat has the potential to transform protein production by significantly reducing its environmental footprint, improving public health, and mitigating the ethical and social impacts of conventional meat. Achieving price parity is a critical step toward realizing these public benefits at scale, and amino acid cost and supply challenges must be addressed to unlock the full potential of cultivated meat. To that end, coordinated action is needed across the ecosystem.

The following calls to action outline specific steps that amino acid suppliers, researchers, cultivated meat companies, policymakers, and nonprofits can take to accelerate progress and ensure a resilient, affordable, and scalable amino acid supply chain for cultivated meat.

Amino acid suppliers

1. Actively monitor global cultivated meat production and proactively plan capacity to meet growing amino acid demand, especially for at-risk amino acids (e.g., asparagine, glutamine, histidine, proline, serine, and tyrosine).
2. Improve fermentation productivity and yields for high-risk amino acids such as arginine, asparagine, glutamine, histidine, proline, serine, and tyrosine.
3. Alongside CM companies and regulatory experts, support the co-development of "CM-grade" amino acid input specifications that are fit-for-purpose, standardizing criteria for endotoxin thresholds, heavy metals, microbial contamination, and other impurities of concern, to streamline documentation and regulatory review.
4. Share production volumes for amino acids. The true production volume of most amino acids suitable for cultivated meat is not currently known, and improved data will be necessary to continually refine which amino acids may be limited in supply.
5. Share updated life cycle inventory data for real-world, food- and feed-grade amino acid production and integrate renewable energy to reduce environmental impact.

Academic researchers

1. Develop and publish empirical data from commercially relevant bioprocesses to refine the feed conversion ratio of cultivated meat and key substrates such as glucose, glutamine, and other amino acids.
2. Use the hydrolysate modeling framework from this report to narrow the search space for high-potential blends of hydrolyzed raw materials for experimental validation.
3. Develop hydrolysis protocols that make hydrolysates a cost-competitive amino acid source ($1.51–$11.27/kg hydrolysate) compared with fermentation-derived amino acids.
4. Generate open-access datasets on hydrolysate composition and performance to enable artificial intelligence (AI) and machine learning (ML) tools for media optimization.
5. Collaborate with amino acid suppliers to update environmental impact data for food- and feed-grade amino acid production and integrate it into future LCA models.
6. Investigate metabolic and cell engineering strategies to improve fermentation yields and CM feed conversion ratios, reducing the cost burden of high-impact amino acids such as arginine, asparagine, glutamine, histidine, proline, serine, and tyrosine.

Cultivated meat companies

1. Co-develop “CM-grade” amino acid standards with amino acid suppliers, establishing fit-for-purpose criteria for amino acid quality to streamline documentation and regulatory compliance. Foregoing such an effort in favor of defaulting to higher-grade inputs could unnecessarily constrain innovation and prevent cost-competitive production at commercial scales.
2. Publish commercially relevant media formulations, including differentiation media, to improve shared modeling and supply chain planning.
3. Publish empirical data from commercially relevant bioprocesses to determine the feed conversion ratio of cultivated meat and key substrates such as glucose, glutamine, and other amino acids.
4. Explore hybrid media strategies that integrate hydrolysates and fermentation-based amino acids for long-term cost and sustainability gains.
5. Collaborate across the sector to establish pooled procurement strategies that create clear, aggregated demand signals for high-risk amino acids. Parallel development of CM-grade standards can ensure the entire supply chain is operating under the same expectations.

Governments, policymakers, and regulatory agencies

1. Support the development and recognition of “CM-grade” amino acid standards to streamline regulatory reviews and enable cost-effective sourcing.
2. Establish global leadership in cultivated meat by creating incentives for domestic amino acid manufacturing, including de-risking CapEx burden through grants, tax incentives, and low-interest loan programs. Onshoring amino acid manufacturing can reduce the dependence and risk of relying on concentrated international supply chains while creating new jobs and economic opportunities to leverage local biomass and feedstocks for amino acid fermentation.

Nonprofits and trade associations

1. Acquire and open-source media formulations and other IP (e.g., cell lines and bioprocess data) from defunct startups to support sector-wide transparency and modeling.
2. Facilitate pre-competitive R&D by funding projects that validate hydrolysate blends, optimize raw material sourcing and processing, and characterize functional performance.
3. Convene stakeholders to finalize and promote adoption of “CM-grade” media input standards and help align industry expectations with regulatory needs.
4. Support the creation of shared databases for amino acid production volumes, hydrolysate performance, and environmental impacts to guide future modeling and investment.

Abbreviations

AA	amino acid
AI/ML	artificial intelligence/machine learning
CHO	chinese hamster ovary cells
CM	cultivated meat
CoA	certificate of analysis
DM	dry mass
EU	European Union
FSF4	name of a media formulation from SciFi Foods, acquired by GFI
g AA/kg CM	grams of amino acids per kilogram of cultivated meat
IP	intellectual property
kTA	kilotonnes annually
L	liter
LCA	life cycle assessment
MT	metric ton = tonne
MT/yr	metric tons per year
R&D	research and development
Spiked AAs	fermentation-derived amino acids (arginine, asparagine, cystine, glutamine, and serine) assumed to be added individually to media during the hydrolysate analysis portion of the report
TCA	Tricarboxylic Acid
TEA	techno-economic analysis

Table of contents

Introduction

Cultivated meat is a method of meat production that involves the cultivation of animal cells in a controlled environment. This approach presents the opportunity to feed more people with fewer resources, meeting the growing global demand for protein in a more sustainable, efficient, and humane way. One of the major challenges for the cultivated meat sector is lowering the cost of production. Prior techno-economic analyses have identified the cell culture media as a major cost driver (Humbird 2021; Negulescu et al. 2023; Vergeer, et al. 2021). Within the cell culture media, amino acids are a leading cost component, with one well-cited study calculating that they would contribute ~$18 to $19/kg to the cost of production, making most cultivated meat processes economically nonviable (Humbird 2021).

In animal cell cultures, 13 L-amino acids are essential and must be provided exogenously to the cells. In cell culture media used to cultivate rapidly proliferating and dense cultures, other non-essential amino acids or chemical forms (e.g., dipeptides) of amino acids are included to handle the metabolic demand. Accordingly, most complete cell culture media typically contain at least 20 amino acids or amino acid forms in varying quantities.

Amino acids can be produced from several different methods, including the extraction of protein hydrolysates, chemical or enzymatic synthesis, and microbial fermentation (D'Este et al. 2018). Microbial fermentation is the predominant form of current industrial production of L-amino acids, with workhorse organisms such as *E. coli* and *C. glutamicum* used to produce the bulk of those available. Despite this, researchers have hypothesized that supplying amino acids and other nutritional components of the media (e.g., vitamins, sugars, minerals) through hydrolyzed crops, microbes, microalgae, or other agricultural sidestreams could be more cost-effective and environmentally sustainable than individual fermentation processes (Humbird 2021; Sinke et al. 2023; Eastham et al. 2023).

This analysis aims to clarify the current and future amino acid supply chain for cultivated meat. Using structured interviews with amino acid suppliers, cell culture media companies, cultivated meat manufacturers, hydrolysate producers, and industry experts, we collected information on amino acid prices, production volumes, sourcing practices, and regulatory considerations. Combined with publicly available information on media formulations and bioconversion efficiency projections, we modeled amino acid supply assuming a future cultivated meat industry producing 250 kilotonnes of product annually (250 kTA). This model served as the basis for evaluating:

- How many tonnes of total and individual amino acids are needed to meet a 250 kTA demand?
- What is the anticipated cost contribution of amino acids per liter of media and per kg of cultivated meat, and how does this compare to prior estimates?
- Which raw materials or hydrolysates are the most promising candidates for supplying amino acids, and what would they need to be priced at to be competitive with amino acids from fermentation?

Using this information, we provide crucial insights into potential supply chain bottlenecks, highlight areas for research and development, and propose recommendations for stakeholders along the amino acid supply chain. This report provides the most complete assessment to date of the amino acid supply chain for cultivated meat based on current practices and future needs.

Methods (abridged)

The analysis aimed to evaluate the following questions:

- How many tonnes of total and individual amino acids are needed to meet a 250 kTA CM demand?
- What is the anticipated cost contribution of amino acids per liter of media and per kg of cultivated meat, and how does this compare to prior estimates?
- Which raw materials or hydrolysates are the most promising candidates for supplying amino acids, and what would they need to cost to be competitive with amino acids from fermentation?

Structured interviews

A detailed questionnaire was assembled, and a total of 25 stakeholders (Eight CM companies, three hydrolysate suppliers or experts, 10 cell culture media companies or experts, four amino acid suppliers or experts) were interviewed and/or provided written answers to the questionnaire. Information acquired from interviews was used to inform the Scenarios. All information is based on aggregated responses, and any identifying information was excluded to ensure the confidentiality of participants.

Scenarios

1. Eight bioconversion efficiencies were used to estimate the amount of amino acids required to make 1 kg of cultivated meat. The range of estimates used throughout the analysis spanned 200 to 650 g AA/kg CM.
2. The concentrations of total and individual amino acids were taken from commercially relevant media formulations to understand the demand for amino acids. A media formulation called FSF4, previously developed by the CM startup SciFi Foods and acquired by GFI, was used as the baseline formulation. Some scenarios and figures also incorporated a modified CHO media formulation to represent a nutritional profile that can support multiple species, and a higher upper bound for nutritional density.
3. Three amino acid price scenarios were assembled (**Table 1**). These scenarios included two food-grade amino acid price tiers based on real-world quotes and one feed-grade price tier derived from aggregate supplier data. Some scenarios also incorporated previously published pricing data (Humbird 2021). The Extended Methods in the Appendix contain further details on how each price scenario was established.

Table 1. Scenarios for food- and feed-grade amino acid prices used in this study. The low food-grade scenario represents a -25% differential from the lowest value listed for each amino acid in the quotes obtained during interviews, while the high food-grade scenario represents a +25% differential from the highest price for each amino acid listed in quotes. A hypothetical low price was obtained for feed-grade amino acids listed on aggregate supplier sites. All values were rounded to the nearest whole number.

Amino acid	Price ($/kg AA)		
	Feed-grade price scenario	Low food-grade price scenario	High food-grade price scenario
L-Alanine	5	13	21
L-Arginine	3	5	18
L-Asparagine	13*	18	31
L-Aspartic Acid	3	10	16
L-Cysteine	10	11	29
L-Cystine	10	13	13[θ]
L-Glutamic Acid	4	12	20
L-Glutamine	5	7	16
Glycine	2	4	7
L-Histidine	10	26	75
L-Hydroxyproline	15*	15	25[θ]
L-Isoleucine	4	11	19
L-Leucine	4	4	6
L-Lysine	1	4	11
L-Methionine	3[△]	8	20
L-Phenylalanine	8	8	13
L-Proline	13	19	31
L-Serine	10	30	50
L-Threonine	1	3	13
L-Tryptophan	3	16	33
L-Tyrosine	10	14	30
L-Valine	3	4	13

* No feed-grade prices were obtained for these amino acids, so the lowest food-grade value was used.

△ Feed-grade methionine is produced as D,L-Methionine, which may not be suitable for animal cell culture due to a lack of the liver and kidney enzyme D-amino acid oxidase used to convert D-amino acids *in vivo.* Prices for pure L-Methionine are uncertain.

θ No real-world quotes were obtained for these amino acids, so the highest food-grade value from aggregate suppliers was used.

Identifying candidate hydrolysate blends and costs

Amino acid composition (g AA/100 g dry mass) was assembled for 50 different raw materials or commercially available hydrolysates. The raw materials and hydrolysates were determined to be an inadequate supply of glutamine, arginine, asparagine, cystine, and serine based on the requirements of the media formulations. These five amino acids (Spiked AAs) were assumed to be supplied individually via fermentation processes.

ChatGPT (GPT-5) was used to identify candidate blends (combinations of up to three raw materials or hydrolysates) that would satisfy the requirements for the remaining amino acids in the media. Results were replicated using Excel's Solver tool and verified by manual calculation. Maximum viable prices for the hydrolysate blends to achieve parity with a fully fermentation-derived amino acid media composition were then calculated.

The Appendix contains the Extended Methods section, including the full interview questionnaire, FSF4 media formulation, and key assumptions and limitations. If you are a cultivated meat researcher, we highly recommend reading through the Extended Methods, which contains further background, references, details, figures, and tables related to the scenarios and methodology used throughout the analysis.

Excel spreadsheets used for the analysis can be downloaded here. The spreadsheet also contains multiple interactive calculators for amino acid costs and hydrolysate blending.

Photo credit: samuelgarces / Adobe Stock

Results

Total amino acid requirements

Amino acid suppliers and other industry stakeholders may benefit from understanding the expected total quantity of amino acids needed to produce a given amount of cultivated meat. In this analysis, we modeled a future 250 kTA cultivated meat industry, which is approximately 500x the annual commercial production volume capacity in 2025, based on internal GFI data. Using eight bioconversion efficiency scenarios ranging from 200 to 650 g AA/kg CM (**Table A1, Extended Methods**), a straightforward calculation results in an expected range of ~50 to 163 kTA of total amino acids (**Figure 3**).

Individual amino acid requirements

The quantity of each individual amino acid that would be required to produce 250 kTA of cultivated meat was estimated by scaling the amino acid amounts in the FSF4 media formulation to match the total amino acid requirements per kilogram of meat, based on the full range of bioconversion efficiency scenarios (200-650 g AA/kg CM). An additional scenario using the modified CHO media and the least efficient scenario (650 g AA/kg CM) was calculated to display the higher upper-bound and potential variability in certain amino acid requirements (**Figure 4**).

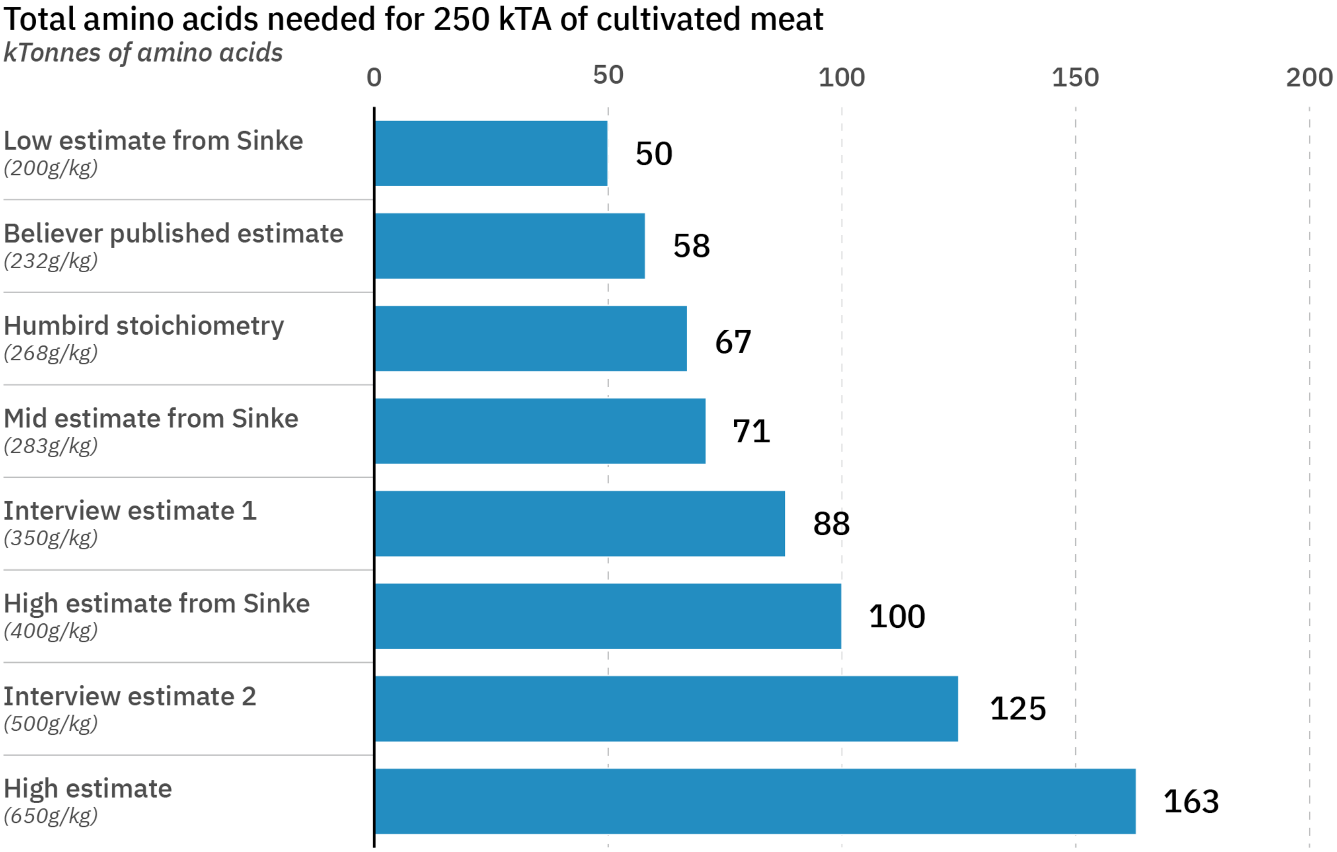
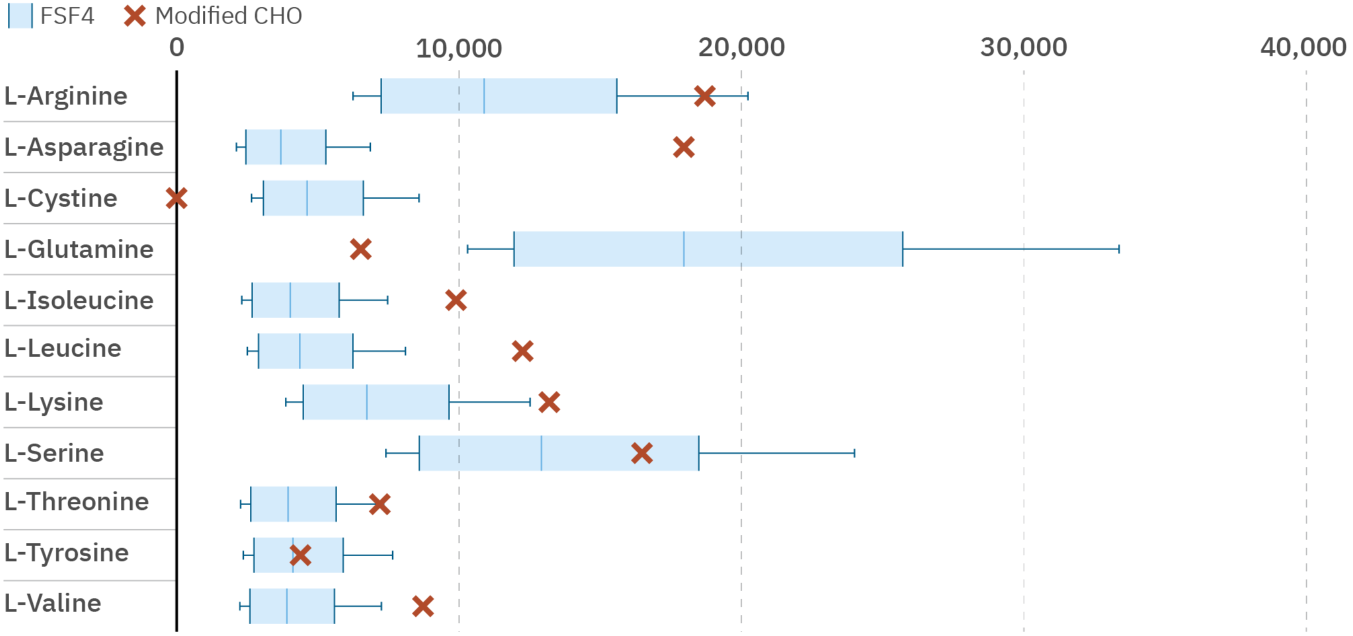


Figure 3. Projected total amino acid requirements to produce 250 kTA of cultivated meat. Here, we scaled the projected amino acid needs to 250 kTA of cultivated meat using eight bioconversion efficiency estimates (g AA/kg CM). This comparison illustrates the magnitude of total amino acid demand at an industrial scale. See Table A1 for references.

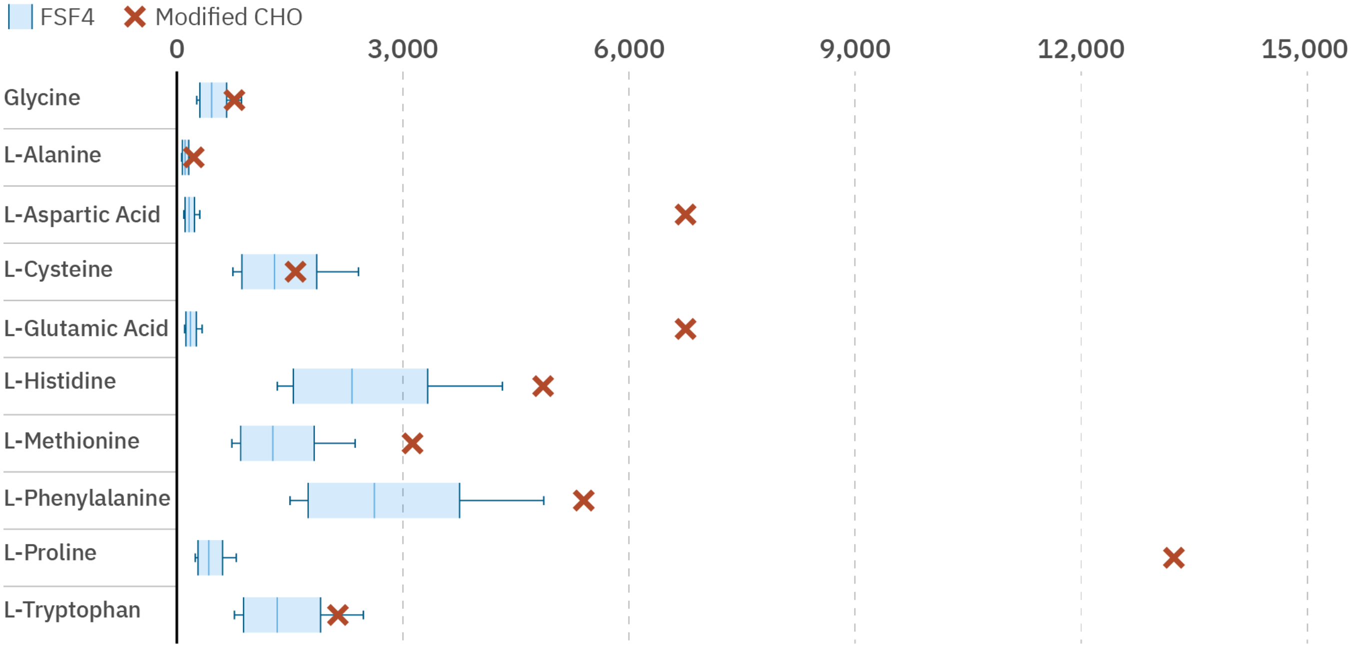
Amino acid requirements for 250 kTA cultivated meat production—high volume amino acids (tonnes of AA)



Note the change of the x-axis scale, for ease of viewing, from 40,000 tonnes in 4a to 15,000 tonnes in 4b

Figure 4A

Amino acid requirements for 250 kTA cultivated meat production—low volume amino acids (tonnes of AA)



Note the change of the x-axis scale, for ease of viewing, from 40,000 tonnes in 4a to 15,000 tonnes in 4b

Figure 4B

Figure 4. Estimated volumes (MT) of individual amino acids needed to produce 250 kTA of cultivated meat across the full range of bioconversion efficiency scenarios (200-650 g AA/kg CM). The blue data correspond to the FSF4 media formulation. The red data correspond to the modified CHO formulation using the least efficient scenario (650 g AA/kg CM). (A) shows high-volume amino acids, defined as those with potential requirements reaching 5,000 MT or more. (B) shows lower-volume amino acids, generally requiring less than 5,000 MT. Together, these figures highlight both the scale and variability in amino acid demand across different production scenarios and media compositions. (Note the change of the x-axis scale, for ease of viewing, from 40,000 tonnes in 4a to 15,000 tonnes in 4b.)

This provided a clear view of which amino acids would be required in the largest quantities and highlighted the variability in demand across different modeling assumptions.

The data show that arginine, glutamine, and serine had the highest projected demand, with volumes often exceeding 10,000 MT annually. Eight other amino acids (asparagine, cystine, isoleucine, leucine, lysine, threonine, tyrosine, and valine) were characterized as high volume, with minimum requirements of at least 2,200 MT annually. The remaining 11 amino acids had projected volume requirements in the hundreds to low thousands of MT annually. Notably, some amino acids are absent (e.g., cystine, hydroxyproline) or considerably divergent (e.g., asparagine, glutamic acid, aspartic acid, proline) in the FSF4 and modified CHO formulations, suggesting uncertainty for these projections. Public disclosure of additional commercial CM media formulations can provide higher confidence in the degree of inclusion of these inputs.

Individual amino acid supply bottlenecks

Using these data, we cross-referenced current amino acid production volume information obtained from literature and during the interview stage (**Table 2**) to determine which amino acids could be at risk of supply constraints as the cultivated meat industry scales toward industrial volumes (e.g., 250 kTA and beyond). Although exact current production volume data is opaque and of lower confidence (and further complicated by the lack of stratification by downstream usage in feed, food, and pharma), the combined modeling data and information gathered suggested multiple amino acids are at high risk of supply bottlenecks due to future estimated demand potentially outstripping current production volumes

Those identified as being high risk to supply bottlenecks included asparagine, glutamine, histidine, proline, serine, and tyrosine, and, to a lesser extent, isoleucine and leucine. Interestingly, while our calculations and the data from **Table 2** did not support the following amino acids as high-risk bottlenecks, they were flagged during interviews and are also worth noting: cysteine, methionine, and tryptophan. Snapshots containing more information on these amino acids are provided in the Appendix section of this paper.

Photo credit: murat / Adobe Stock

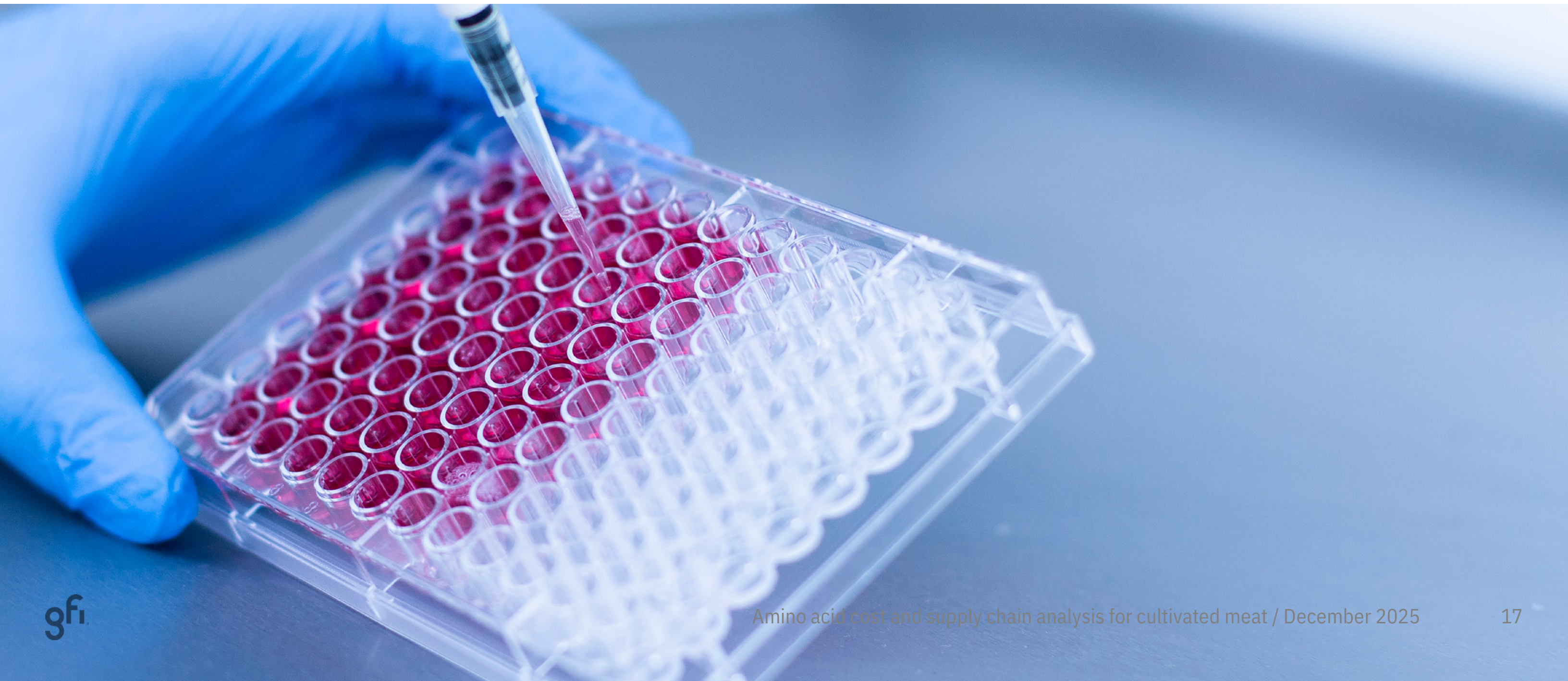


Table 2. Production volume comparisons. Shown are the minimum and maximum estimated annual amino acid requirements to produce 250 kTA CM per our calculations, along with the current estimated yearly global production volumes for each amino acid. Amino acids with the highest supply risk are shaded in dark orange, while those shaded in light orange were deemed moderate risk. Additional details for risk designation are provided in the Appendix. Annual production volume data were compiled from published literature, confidential industry interviews, and market research data. The data have limitations and are considered low confidence.

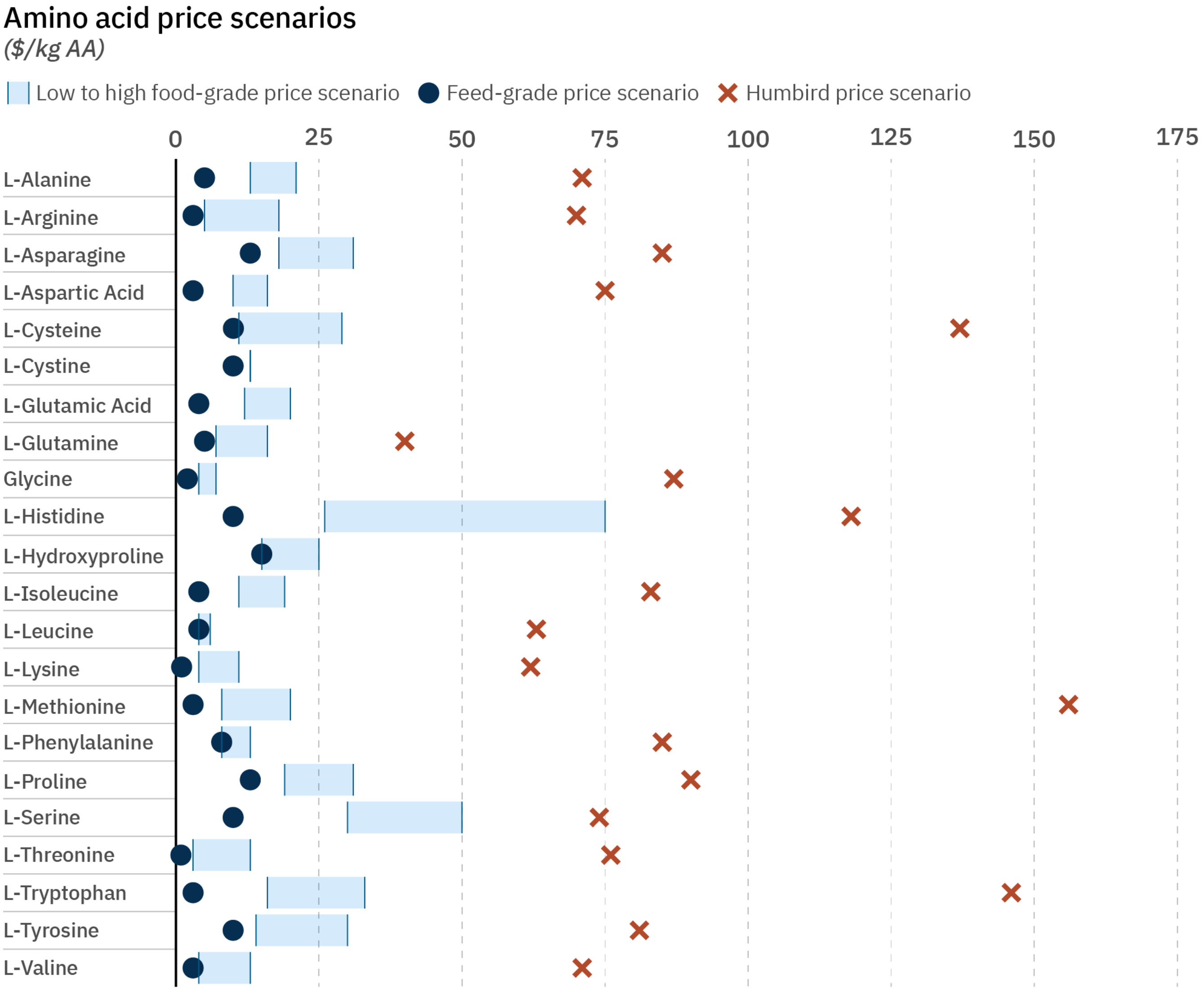
Amino acid	**Minimum Estimate** (MT AA/250 kTA CM)	**Maximum Estimate** (MT AA/250 kTA CM)	**Est Yearly Production** (MT AA)
L-Alanine	63	225	50,000
L-Arginine	6,250	20,244	60,000*
L-Asparagine	2,119	18,000	N/A
L-Aspartic Acid	94	6,750	17,000
L-Cysteine	744	2,410	11,650
L-Cystine	0	8,589	N/A
L-Glutamic Acid	104	6,750	3,300,000
L-Glutamine	6,525	33,398	8,000*
Glycine	265	858	70,000
L-Histidine	1,334	4,860	2,000*
L-Isoleucine	2,308	9,900	3,000
L-Leucine	2,502	12,263	3,000
L-Lysine	3,867	13,208	2,200,000
L-Methionine	731	3,128	850,000**
L-Phenylalanine	1,503	5,400	30,000
L-Proline	244	13,230	500
L-Serine	7,416	24,019	400
L-Threonine	2,265	7,336	950,000
L-Tryptophan	764	2,476	90,000*
L-Tyrosine	2,364	7,657	200
L-Valine	2,240	8,730	20,000*

* Per interviews.

** The vast majority of this volume is believed to be feed-grade methionine, produced as D,L-Methionine, which may not be suitable for animal cell culture due to a lack of the liver and kidney enzyme D-amino acid oxidase used to convert D-amino acids *in vivo*. Volumes of pure L-Methionine are unknown.

Amino acid costs for media and cultivated meat production

Humbird's techno-economic analysis was instrumental in identifying amino acids as a cost driver of cultivated meat production, with projections (based on an amino acid price to 100 kTA CM volume relationship) suggesting that amino acids alone could contribute ~$18-19/kg CM. However, many in the industry questioned the validity of these estimates. Accordingly, we sought to develop updated price information for amino acids using data from media manufacturers, cultivated meat companies, and verified supplier quotes (**Table 1**; see Extended Methods). The updated data show that real prices for food-grade amino acids are, in some cases, over an order of magnitude lower than those used previously (**Figure 5**). As noted by interviewees, Humbird's previous estimates were more reflective of pharma-grade prices. This large discrepancy has implications for the projected cost contribution of amino acids per liter of media and per kg of CM.



Amino acid price scenarios
($/kg AA)

Figure 5. Current amino acid price data based on quotes and other information obtained during interviews. The light blue bars represent the low to high food-grade price ranges calculated from quotes. Feed-grade estimates are shown in dark blue dots, with Humbird's estimates shown in red. Cystine, glutamic acid, and hydroxyproline were not included in the Humbird stoichiometry. See Table 1 caption for caveats to the data for asparagine, cystine, hydroxyproline, and methionine.

Total amino acid cost contribution per liter of media

Previous work has estimated that media costs would need to approach $1/L or less to have a chance at being competitive with most conventional meat products (Negulescu et al. 2023). Interestingly, a recent peer-reviewed study by Believer Meats reported media costs at $0.63/L (Pasitka et al. 2024). However, even more recent reports from CM companies Meatly and GOURMEY suggest media costs are already around $0.20/L, with Clever Carnivore reporting the lowest cited costs at $0.07/L. To understand how this could be achieved, we calculated the amino acid cost contribution to the FSF4 and modified CHO cell media using the three price estimates gathered in this study alongside Humbird's prices for comparison (**Figure 6**). Total amino acid costs for the FSF4 media were between ~$0.02 to $0.08/L, while the more nutritionally dense CHO media had costs between ~$0.05 to $0.17/L. Notably, the higher prices assumed by Humbird place amino acid costs at ~$0.24 to $0.54/L for the respective media formulations, falling outside the $0.20/L benchmark for total media costs.

It is important to note that these calculations reflect only the amino acid portion of the media. Other components, such as growth factors, vitamins, minerals, salts, carbohydrates, and lipids, are not included in this analysis. Besides amino acids, other studies have identified growth factors and other recombinant proteins (e.g., albumin, insulin, and transferrin) as cost drivers within media (Swartz et al. 2023). However, trends in the industry suggest many companies have developed protein-free media, exemplified by a recent cultivated chicken product produced by Believer Meats that was cleared for sale in the United States (FDA Inventory for Human Food Made with Cultured Animal Cells, 2025).

Amino acid cost contributions to FSF4 and modified CHO media
($/L)

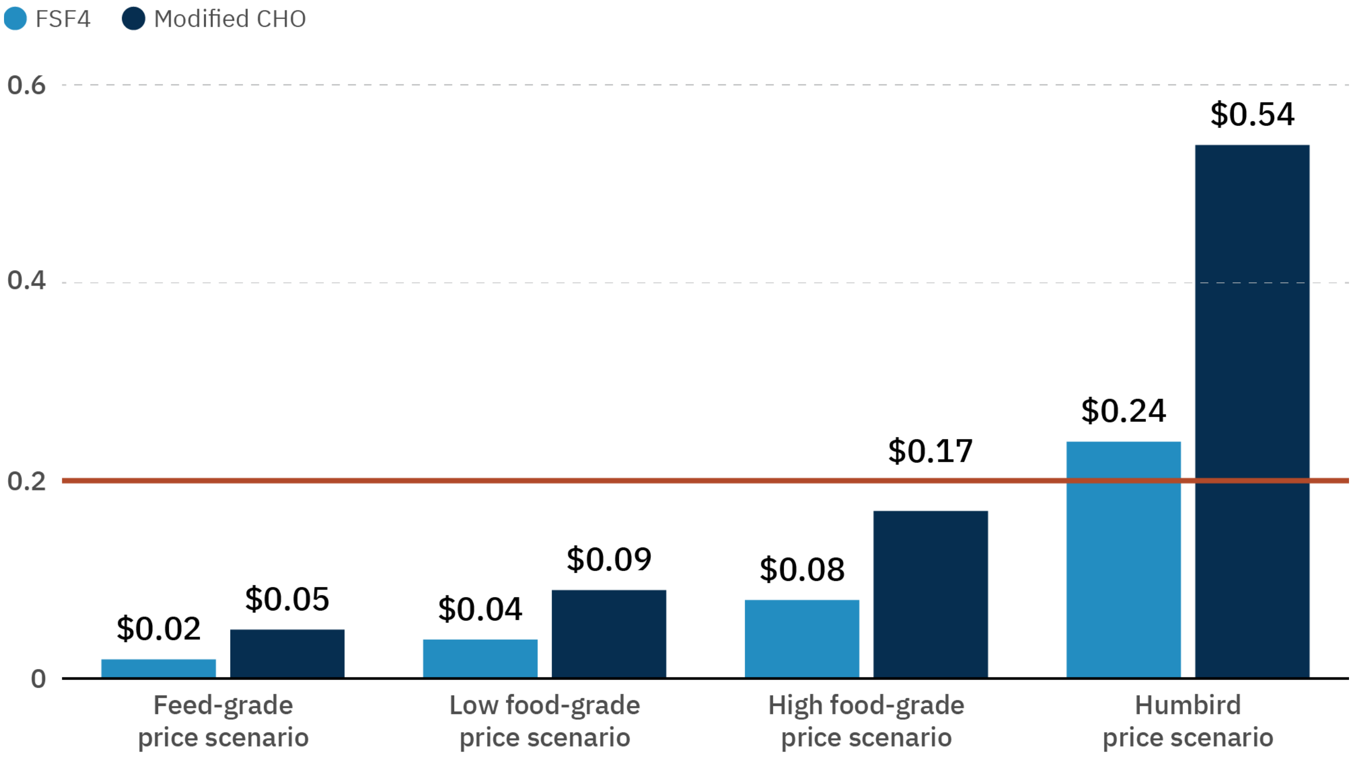


Figure 6. Total amino acid cost contributions to FSF4 media and modified CHO media formulations across four different price scenarios. Each figure displays the per-liter contribution of total amino acids across these price assumptions, with a reference line in red set at $0.20/L—an approximate near-term media cost target for the industry. For ease of comparison, the Humbird price estimates were applied to the media formulations used in this study, rather than the stoichiometry used in his study.

Protein-free media may be difficult to achieve for all the cell types used in cultivated meat and, as a result, proteins may be present in other formulations. Although growth factor and protein prices are currently high when used, they are not anticipated to be a long-term cost driver for the industry. Furthermore, other work has reported that amino acids make up ~76% of media costs, with glucose, vitamins, lipids, and salts contributing less than 1% of total media costs (Negulescu et al. 2023). Accordingly, our analysis suggests that achieving media costs below $0.20/L is quite reasonable. Future studies can follow the strategy outlined in this report to determine a more accurate accounting of complete media costs.

Individual amino acid cost drivers

In addition to total amino acid costs, we identified individual amino acids that are potential cost drivers, defined as those accounting for nearly 10% or more of the total amino acid cost contribution under any of the pricing scenarios and media formulations (**Figures 7-8**). Arginine, asparagine, histidine, and serine were found to be cost drivers across both media formulations, while glutamine and cyst(e)ine[1] were only flagged as high-cost contributors in the FSF4 media, and proline was only identified as high-cost in the modified CHO media. Serine stood out, accounting for between ~16-38% of total amino acid costs, depending on price scenario and media formulation. The reasoning for their high costs is due to a combination of high inclusion rates and/or high prices (see “High-risk amino acid snapshots” in the Appendix).

The difference in cost drivers between the two formulations reflects their distinct amino acid compositions that match the metabolism of the cells for which they were designed. In the FSF4 media, the higher glutamine concentration makes glutamine a major cost driver, whereas in the modified CHO media, glutamine is present at a lower level and is partially “replaced” by increased asparagine. This shift reflects the fact that the modified CHO media formulation is intended to cover a range of species with potential for cultivated meat applications, some of which synthesize asparagine less efficiently and therefore require higher supplementation. In addition, there are species-specific differences in nitrogen metabolism. For example, poultry cells rely less on glutamine and generate lower levels of ammonia, instead using asparagine more heavily as both a carbon source and a nitrogen donor for the TCA cycle and biosynthesis (Lohr et al. 2014). Consequently, asparagine represents a larger fraction of total amino acid costs in the modified CHO media.

Proline supplementation in CHO media is likely driven by CHO cells frequently lacking a fully functional proline biosynthesis pathway due to defects in relevant enzymes. This necessitates added proline to sustain robust growth and high recombinant productivity (Valle et al. 1973). In contrast, future cultivated meat cell lines may not require this level of proline supplementation, illustrating that amino acid demands are both cell line- and process-specific. This highlights the need for targeted media development and systematic evaluation of amino acid requirements for each cell line used in production, rather than assuming that optimized formulations will translate directly to other species or applications.

---

[1] Cyst(e)ine was only a cost driver under a single condition and was deemed to be lower concern.

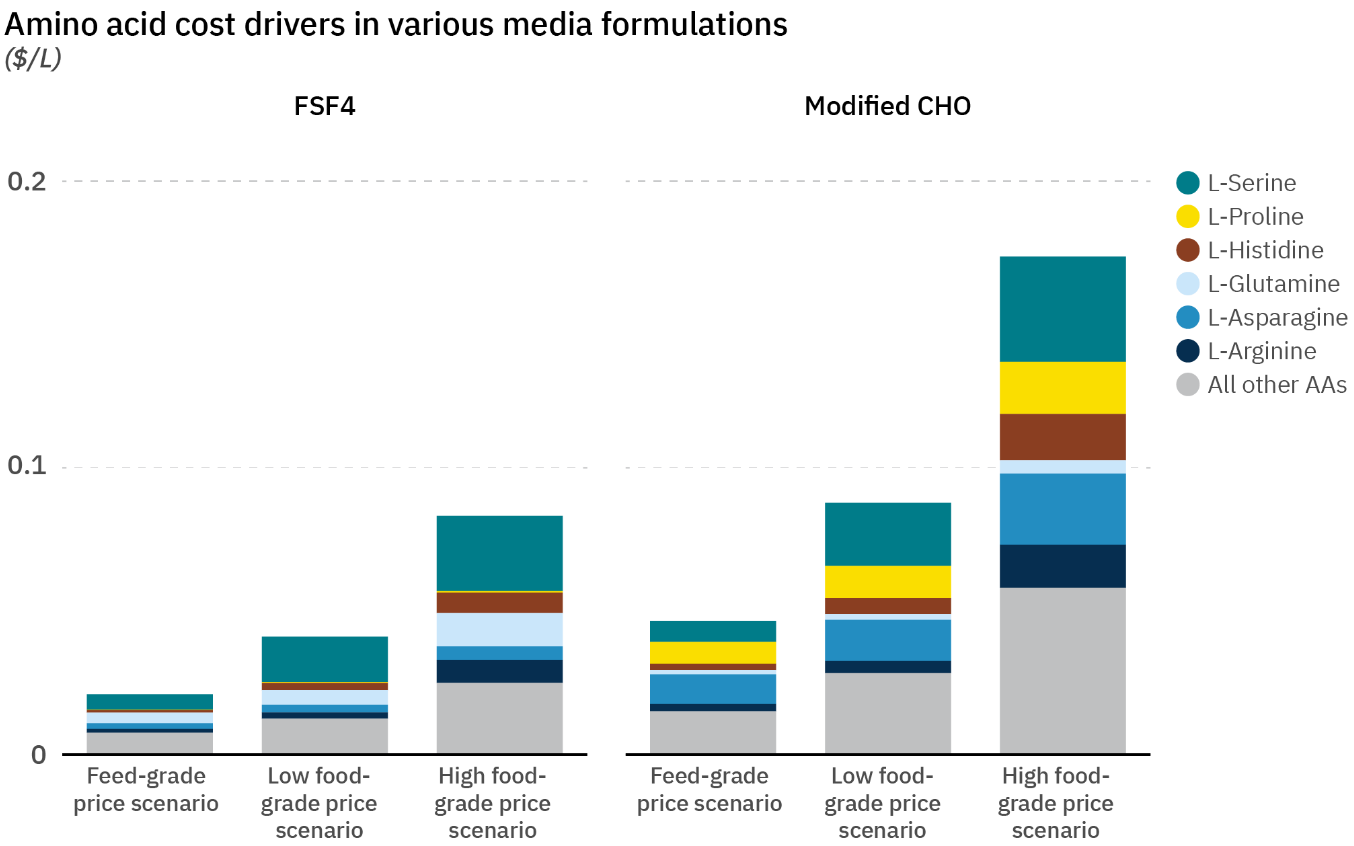
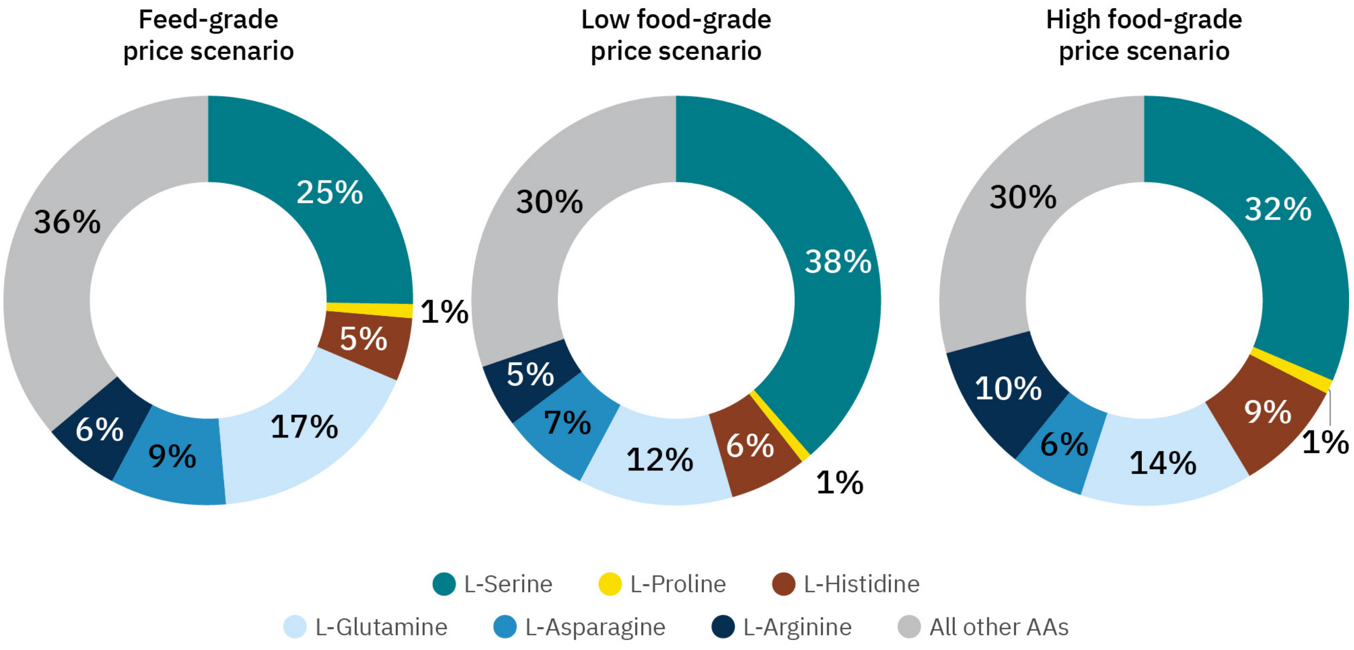


Figure 7. Amino acid cost drivers in FSF4 and CHO media across multiple pricing scenarios. This figure highlights the individual amino acids that contribute most significantly to cost: serine, proline, histidine, glutamine, asparagine, and arginine.

FSF4



Modified CHO

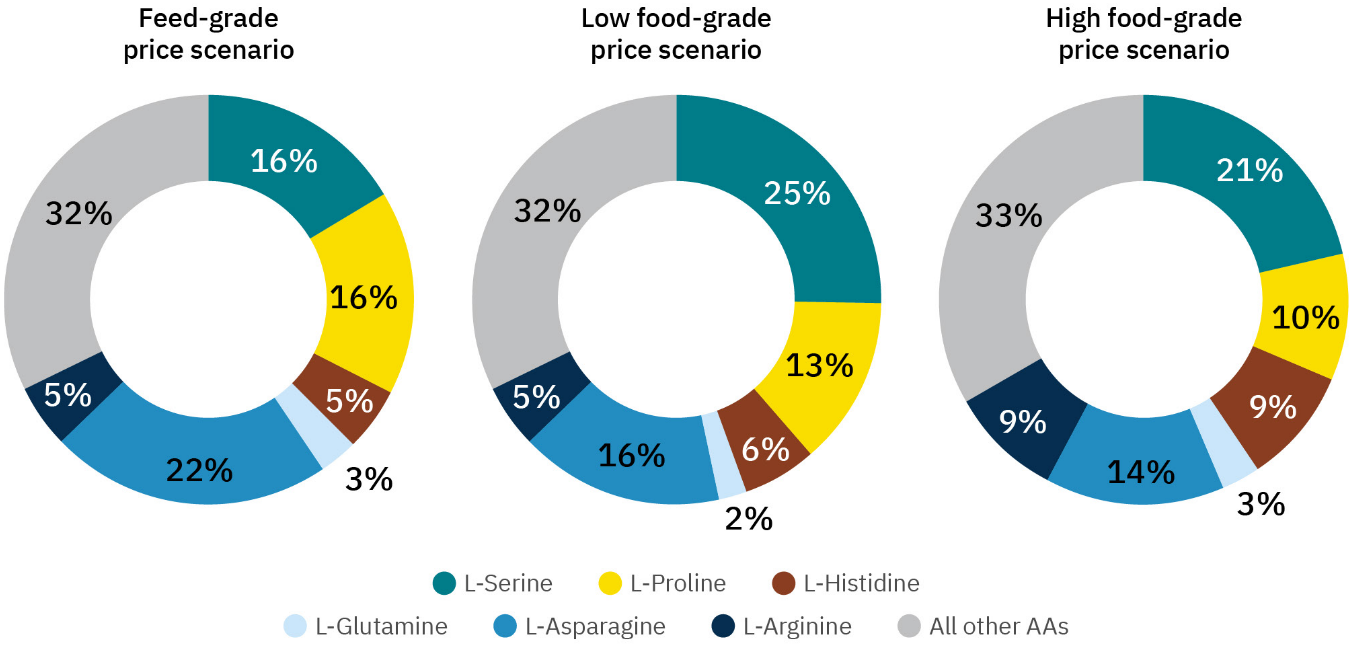


Figure 8. Percent of the cost contribution of amino acid cost drivers in (Top) FSF4 media and (Bottom) modified CHO media cost across multiple pricing scenarios.

Amino acid cost contributions per kilogram of cultivated meat

The cost per liter of media ($/L) is a widely used metric across the cellular agriculture sector, but can be prone to misinterpretation. Comparing this metric and translating it to the cost of the end product requires additional contextual information on the nutritional density of the ingredients, the total volume required to make a given quantity of meat, and the bioconversion efficiency of the cells and process. As this information is captured by the media formulations and bioconversion efficiency estimates in this study[2], we proceeded to model amino acid cost contributions per kg CM. Then, we compared these results to previous estimates from Humbird, as well as a hypothetical $10/kg CM target benchmark (**Figure 9**).

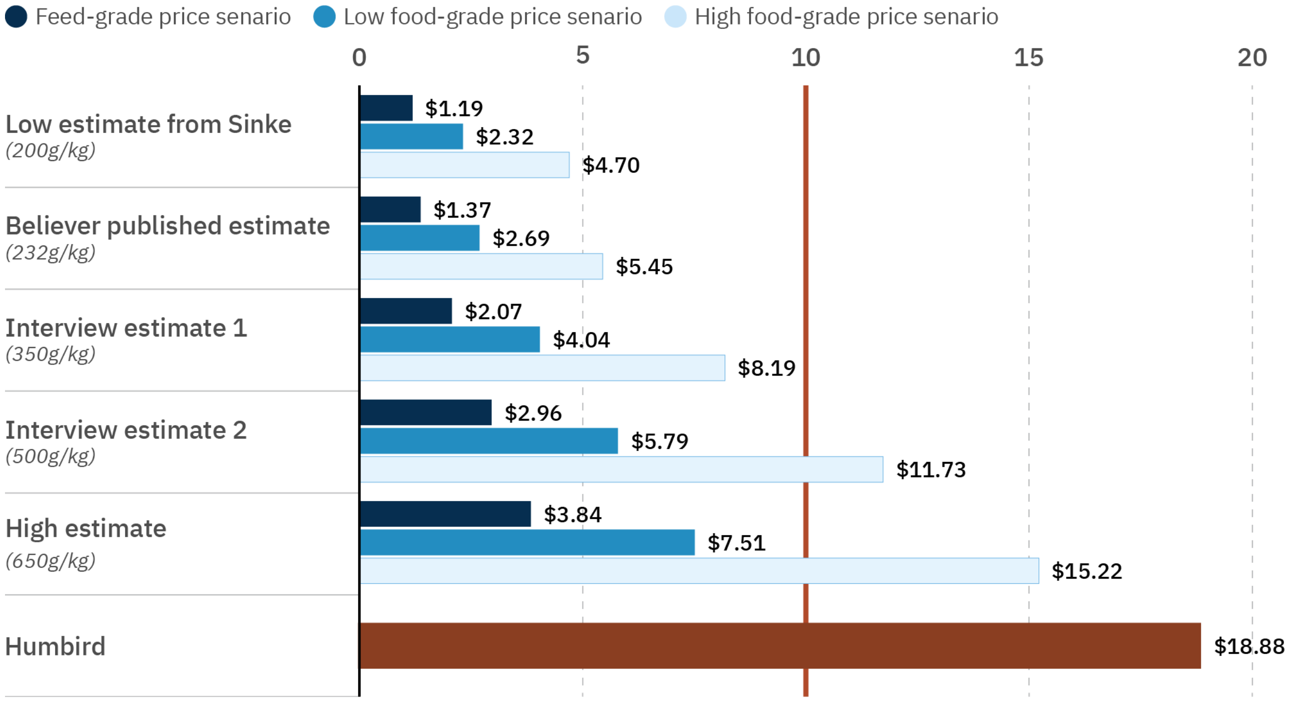
The analysis revealed that for both media formulations, amino acid costs remained under $10/kg CM across all three price tiers for the most efficient bioconversion estimates (200, 232, and 350 g AA/kg CM). As bioconversion efficiency decreases, some estimates (500 and 650 g AA/kg CM) exceeded the $10/kg threshold at the higher price scenario. If the industry is able to source amino acids at the lower end of the price range and achieve efficient bioconversion, then amino acid cost contributions could be held below ~$5/kg CM, significantly less than the ~$18-19/kg CM previously estimated by Humbird. While these calculations exclude all of the other aspects that make up the total cost of CM production, updated pricing for amino acids suggests that the outlook for cost-competitive cultivated meat is more optimistic than previously believed.

Taken together, our analysis suggests that media costs below $0.20/L are likely feasible, while several estimates suggest total amino acid costs may contribute less than $5/kg CM. Despite differences in the amino acid composition between the media formulations, the overall amino acid cost contributions are relatively similar, suggesting that amino acid costs are more sensitive to assumptions made for bioconversion efficiency. The analysis also highlighted serine as a predominant cost driver, accounting for ~16-38% of total amino acid costs, while arginine, asparagine, glutamine, histidine, and proline each accounted for nearly 10% or more of total costs (depending on the estimate or scenario), making them key targets for future cost reduction. Future analyses can apply this strategy to understand other media input cost profiles, further improving the accuracy of media cost and techno-economic models.

> ***Our analysis suggests that media costs below $0.20/L are likely feasible, while several estimates suggest total amino acid costs may contribute less than $5/kg CM.***

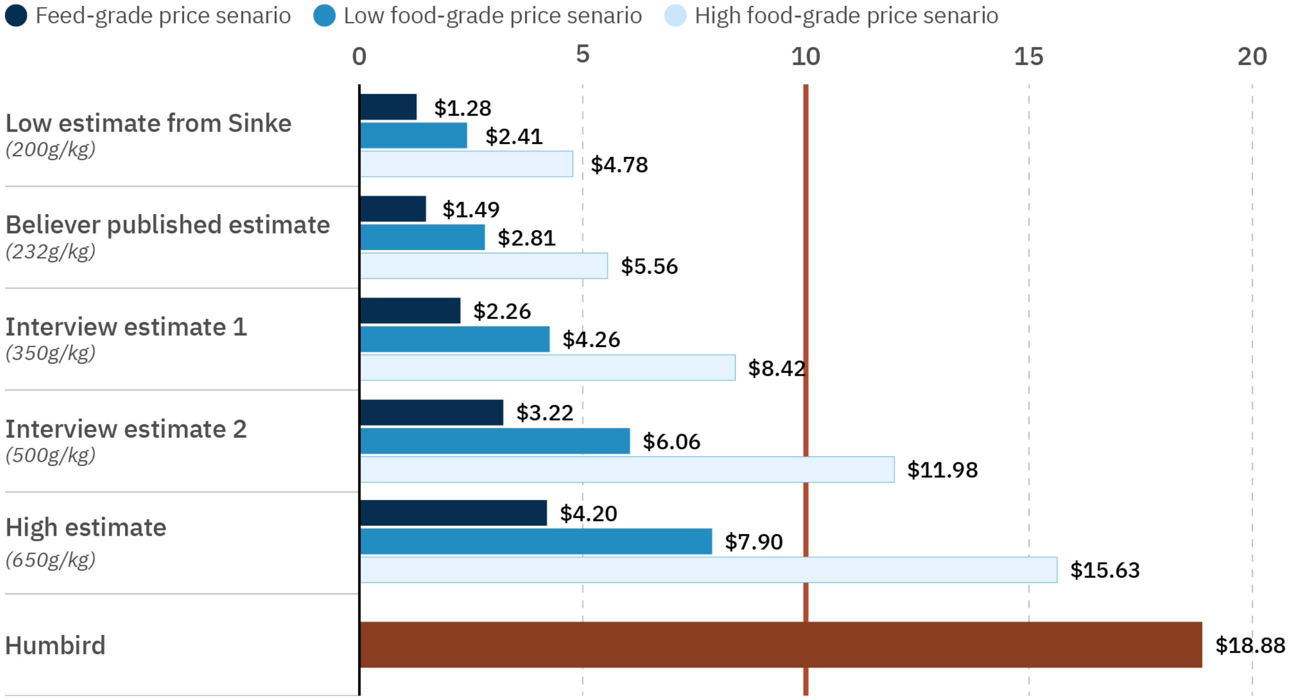
---

[2] The corresponding volumes of media to produce 1 kg of CM (L/kg CM) under different bioconversion efficiency estimates (200-650 g AA/kg CM) work out to ~57-183 L/kg using the FSF4 formulation and ~28-90L/kg using the modified CHO formulation. Limitations are described in **Table A5**.



Total amino acid cost contribution to cultivated meat across bioconversion efficiency estimates and price scenarios—FSF4 media

($/kg CM)



Total amino acid cost contribution to cultivated meat across bioconversion efficiency estimates and price scenarios—modified CHO media

($/kg CM)

Figure 9. Estimated costs of amino acids per kg CM across multiple bioconversion efficiency estimates and pricing scenarios. (Top) Shows estimated costs using the FSF4 media formulation, while (Bottom) uses the modified CHO formulation. Each figure displays how the cost contributions of amino acids per kg CM change depending on the estimated amino acid bioconversion efficiency and price. The red line indicates a hypothetical $10/kg CM target benchmark. For comparison, amino acid costs per kg CM from Humbird's model are shown.

Hydrolysate potential and price thresholds for cultivated meat application

Protein hydrolysates have been proposed as a way to supply cellular nutrition at lower cost and environmental impact (Sinke et al. 2023; Humbird 2021). Below, we review the promises and drawbacks of hydrolysates and analyze which raw materials or hydrolysates could be the most promising candidates for supplying amino acids, as well as what they would need to be priced at to be competitive with amino acids from fermentation.[3]

Industry perspectives and production practices

19 of the 25 interviewees had insights into hydrolysates. Twelve expressed support for hydrolysates as a promising strategy to reduce long-term media costs, three of which are currently blending hydrolysates with purified amino acids. Four companies were cautiously supportive, emphasizing the need for more performance and scale data, while three others were currently uninterested, citing reliability or regulatory concerns.

The appeal of hydrolysates is multifaceted. First, they offer a potential route to lower amino acid input costs. Unlike microbial fermentation, which requires separate production and purification of individual amino acids, hydrolysates can be generated from bulk, protein-rich, and low endotoxin materials in a simplified process, with fewer downstream steps. Some models suggest this could dramatically reduce the per-kilogram cost of amino acid delivery (Humbird 2021).

Second, hydrolysates offer a form of nutrient bundling that may simplify formulation and reduce the need for multiple additive inputs. Promising materials cited by companies included yeast, soy, wheat, pea, cottonseed, and both microalgae and macroalgae. When processed under the right conditions, these materials can yield mixtures of peptides, free amino acids, vitamins, trace minerals, and functional compounds, many of which overlap with the nutritional and signaling needs of animal cells in culture. Their inclusion may reduce the need for extensive quality control across dozens of separate ingredients currently used to formulate cell culture media, while potentially contributing growth-promoting cofactors not yet fully characterized.

Sustainability was also noted as a motivating factor by many companies. Several pointed to the potential to use agricultural sidestreams such as okara, spent yeast, or algal biomass to produce hydrolysates, providing a circular economy pathway and reducing sugar feedstock and land use compared to amino acid fermentation. In this way, hydrolysates could support both economic and environmental sustainability goals for the cultivated meat industry and provide opportunities to leverage region-specific biomass or agricultural sidestreams.

Photo credit: JackF / Adobe Stock

---

[3] Some differences can exist between hydrolysates and peptones. For simplicity, peptones are used interchangeably with hydrolysates throughout this report.

From a production perspective, companies overwhelmingly preferred enzymatic hydrolysis over acid or base methods, citing lower degradation of amino acids, reduced ammonium byproducts, and improved retention of functional peptides. While enzyme costs were noted, most viewed them as justifiable in exchange for improved product consistency and functionality. Downstream processing typically included membrane filtration, centrifugation, evaporation, and spray drying, with a few companies also experimenting with deep eutectic solvent (DES) extraction. Some noted that minimal purification (e.g., without ultrafiltration) may be sufficient to yield cost-effective products with adequate performance.

Despite enthusiasm for the concept, interviewees highlighted key technical and logistical challenges limiting near-term commercial adoption. Several companies emphasized batch-to-batch variability driven by differences in plant source material, seasonality, compositional variability, harvest conditions, and processing methods. They noted that such inconsistencies can have outsized effects at scale, especially in cell lines with narrow performance tolerances, potentially jeopardizing process reliability. Incompatibilities such as filter clogging during media sterilization and elevated ammonia concentrations, likely due to deamidation of proteins and amino acids during hydrolysis, were also reported. Achieving the desired, constant degree of hydrolysis for free amino acids and peptides can require extensive optimization of conditions, including temperature, pH, enzyme type, enzyme/substrate ratio, and time, which may need to be tuned for each raw material and use case. The chemically undefined nature of a hydrolysate and the allergenicity of certain raw materials may lead to increased regulatory burden. Certain materials may also contain residual antinutritional factors that may lead to growth inhibition. Beyond practical and regulatory concerns, there remains a critical lack of research on how variability in hydrolysate composition affects cell performance, as well as a limited mechanistic understanding of which peptide fractions are bioactive.

Critically, our analysis identified several amino acids such as glutamine, asparagine, cystine, and sometimes serine and arginine, as often underrepresented in hydrolysates due to degradation during processing or low native abundance in the source material (**Figure A5, Extended Methods**). These shortfalls likely require targeted supplementation with purified amino acids to meet cellular demands. It is possible that some hydrolysates may still deliver these compounds via protected or peptide-bound forms, such as Ala-Gln or N-acetyl-cysteine, that can act as intracellular reservoirs and contribute to cellular amino acid pools post-uptake; however, this has yet to be verified empirically. Given these limitations, interviewees noted that while there is enthusiasm for hydrolysates and current testing within R&D programs, near-term commercial CM products are unlikely to feature them in their production processes for amino acid supplementation until these challenges are resolved.

Taken together, the interviews suggested that hydrolysates hold long-term promise as a cost-effective and potentially more sustainable alternative to amino acid fermentation. However, until issues around performance consistency, batch variability, and regulatory clarity are addressed, hydrolysates are more likely to serve as supplemental ingredients in hybrid formulations rather than full replacements for amino acids or other basal media inputs. For further discussion of the potential and challenges associated with hydrolysates, we refer the reader to recent review papers (Charteris and le Coutre 2025; Mi et al. 2025).

Identification of candidate hydrolysate blends

Much of the research on hydrolysates to date has been performed through trial and error. Given the large search space of potential starting materials, we sought to develop an updated strategy that narrows the number of hydrolysates to screen and increases the likelihood of identifying experimental hits to further develop. After reviewing the amino acid composition of 50 different raw materials[4] and hydrolysates, we were unable to find a single candidate that could supply all the amino acids needed for our media formulations without using impractical amounts of material (**Figure 10**).

Given these constraints, a more likely pathway for hydrolysates to supplement or fully replace amino acids is through complementary blends, similar to cultural practices of eating beans and rice to deliver complete protein. To identify candidate blends, we used ChatGPT to identify blends of raw materials and hydrolysates that could satisfy the nutritional requirements of the FSF4 or modified CHO media, excluding glutamine, serine, cystine, arginine, and asparagine (the five Spiked AAs; see Methods). The analysis explored blends of up to three materials or hydrolysates across four different scenarios, constrained for simplicity and interpretability (**Table A4, Extended Methods**). The top three hits for each scenario are shown in **Figure 11.**

In Scenario A, top blends based on the FSF4 media at 350 g AA/kg CM required 449–462 g dry mass. Potato and pea peptones were consistent components, complemented by small amounts of yeast extract, papaic soy digest, or pea protein concentrate. This highlights that potato- and pea-derived peptones may be efficient and versatile for meeting amino acid requirements.

Scenario B, which analyzed the modified CHO media blends at the same efficiency, required more dry mass (547–561 g) and showed more variation, including wheat gluten, wheat peptone, and *Yarrowia lipolytica* single cell protein in some blends. Differences from Scenario A were mainly driven by higher proline requirements in the modified CHO media, which could be satisfied by the inclusion of wheat gluten that contains 2-3x more proline than pea or potato peptone. These results show that media-specific amino acid requirements significantly affect optimal blend composition.

Interestingly, Scenario C, which limits inputs to commercially available peptones, produced blends similar to Scenario A (449–465 g) by replacing pea protein concentrate with extra pea peptone. This reinforces the robustness of peptones; however, their use may come at a higher potential cost due to processing requirements, which could affect large-scale economic viability.

Finally, Scenario D, which restricts inputs to raw materials only, required the highest amount of material (678-702 g). This scenario resulted in the most distinct blends, consistently including pea protein concentrate, along with *Yarrowia lipolytica* yeast, wheat gluten, corn gluten meal, and *Chlorella vulgaris*, a type of green microalgae. Despite higher mass requirements, this scenario highlights the potential to expand the diversity of amino acid sources, which may have simpler production processes, lower land use, increased circularity, and other environmental benefits (Haraguchi et al. 2025; Yamanaka et al. 2023; Tuomisto and de Mattos 2011).

---

[4] Raw materials were defined as those that, to the best of our knowledge, were not derived from a hydrolysis process.

Amino acid concentration ratio between peptones/materials and FSF4 media

0 ▨ >1

		L-Alanine	L-Arginine	L-Asparagine	L-Aspartic Acid	L-Cysteine	L-Cystine	L-Glutamic Acid	L-Glutamine	Glycine	L-Histidine	L-Isoleucine	L-Leucine	L-Lysine	L-Methionine	L-Phenylalanine	L-Proline	L-Serine	L-Threonine	L-Tryptophan	L-Tyrosine	L-Valine
Peptone	Pea	8.0	0.2	0.0	14.9	0.1	0.0	21.3	0.0	1.7	0.2	0.2	0.4	0.2	0.1	0.4	2.0	0.1	0.2	0.1	0.2	0.3
	Algae	14.8	0.1	0.0	10.8	0.1	0.0	13.2	0.0	2.4	0.2	0.2	0.3	0.2	0.3	0.3	2.2	0.1	0.2	0.1	0.2	0.3
	Mushroom	4.1	0.0	0.0	3.5	0.0	0.0	3.0	0.0	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.0	0.1	0.1	0.0	0.1
	Guar peptone	2.5	0.1	0.0	1.8	0.2	0.0	4.4	0.0	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.5	0.0	0.0	0.0	0.0	0.1
	Potato peptone	10.1	0.1	0.0	14.7	0.4	0.0	12.8	0.0	2.2	0.2	0.3	0.4	0.2	0.4	0.4	2.4	0.1	0.3	0.1	0.3	0.3
	Wheat peptone	4.3	0.0	0.0	3.2	0.2	0.0	34.7	0.0	1.3	0.2	0.1	0.2	0.0	0.5	0.4	7.5	0.1	0.1	0.0	0.1	0.2
	Bactoeriological malt extract	0.9	0.0	0.0	1.4	0.0	0.0	2.2	0.0	0.2	0.1	0.0	0.0	0.0	0.1	0.1	0.3	0.0	0.0	0.0	0.0	0.0
	Pea peptone	8.8	0.2	0.0	15.0	0.1	0.0	22.7	0.0	2.0	0.2	0.2	0.4	0.2	0.2	0.4	2.1	0.0	0.2	0.3	0.2	0.3
	Pea peptone XG	1.7	0.1	0.0	1.1	0.0	0.0	1.9	0.0	0.1	0.1	0.1	0.2	0.1	0.0	0.2	0.0	0.0	0.1	0.0	0.1	0.1
	Broadbean peptone	7.0	0.1	0.0	11.0	0.1	0.0	15.9	0.0	1.4	0.2	0.2	0.2	0.1	0.2	0.3	1.6	0.1	0.1	0.1	0.2	0.2
	Lupin peptone	4.3	0.1	0.0	9.0	0.1	0.0	17.0	0.0	1.2	0.1	0.1	0.2	0.1	0.1	0.2	1.5	0.1	0.1	0.1	0.2	0.1
	Papaic digest of soybean meal USP	6.1	0.2	0.0	11.7	0.2	0.0	16.9	0.0	2.5	0.4	0.2	0.3	0.1	0.2	0.3	1.9	0.1	0.1	0.1	0.1	0.2
	Papaic soy peptone	6.5	0.2	0.0	2.0	0.0	0.0	4.1	0.0	1.9	0.1	0.0	0.3	0.2	0.3	0.2	0.2	0.1	0.1	0.3	0.2	0.0
	Soy evolution	7.2	0.1	0.0	9.3	0.2	0.0	14.3	0.0	1.5	0.1	0.2	0.2	0.1	0.2	0.2	1.4	0.0	0.1	0.1	0.1	0.2
	Soy peptone crystale	5.8	0.1	0.0	11.0	0.0	0.0	16.5	0.0	1.4	0.1	0.2	0.2	0.1	0.1	0.2	1.8	0.1	0.1	0.1	0.1	0.2
	Soy peptone F	6.5	0.1	0.0	11.0	0.0	0.0	16.2	0.0	1.5	0.2	0.2	0.3	0.1	0.1	0.3	1.7	0.1	0.1	0.0	0.1	0.2
	Yeast extract	10.8	0.0	0.0	9.8	0.0	0.0	15.6	0.0	1.6	0.5	0.3	0.1	0.1	0.6	0.1	1.3	0.0	0.2	0.0	0.2	0.1
	Yeast extract FB	6.1	0.0	0.0	3.8	0.1	0.0	6.4	0.0	0.5	0.2	0.1	0.2	0.1	0.2	0.2	0.5	0.0	0.1	0.1	0.1	0.1
	Yeast extract YB	2.5	0.0	0.0	0.9	0.0	0.0	5.9	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
	Bacteriological yeast extract	17.5	0.0	0.0	10.1	0.2	0.0	16.9	0.0	0.6	0.2	0.2	0.1	0.1	0.4	0.0	0.5	0.0	0.1	0.0	0.1	0.0
Raw material	Pellet	0.3	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
	Kikuyu	0.7	0.0	0.0	0.8	0.0	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
	Alfalfa	0.3	0.0	0.0	0.8	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
	Cotton seed meal	3.5	0.1	0.0	5.1	0.1	0.0	9.4	0.0	0.8	0.1	0.1	0.1	0.1	0.1	0.2	0.8	0.0	0.1	0.1	0.1	0.1
	Tomato pomace	2.0	0.0	0.0	3.1	0.1	0.0	4.0	0.0	0.6	0.1	0.0	0.1	0.0	0.1	0.1	0.6	0.0	0.0	0.0	0.1	0.1
	Canola meal	3.3	0.0	0.0	3.6	0.2	0.0	7.8	0.0	0.9	0.1	0.1	0.1	0.1	0.1	0.1	1.2	0.0	0.1	0.1	0.1	0.1
	Rice bran	2.3	0.0	0.0	2.2	0.0	0.0	3.1	0.0	0.5	0.0	0.1	0.1	0.0	0.1	0.1	0.5	0.0	0.0	0.0	0.0	0.1
	Corn bran	1.6	0.0	0.0	1.0	0.0	0.0	2.1	0.0	0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
	Corn DDGS	0.4	0.0	0.0	0.3	0.0	0.0	0.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
	Corn DDGS (v2)	4.7	0.0	0.0	2.9	0.1	0.0	6.1	0.0	0.7	0.1	0.1	0.2	0.0	0.1	0.1	1.4	0.0	0.1	0.0	0.1	0.1
	Corn gluten meal	12.9	0.0	0.0	6.0	0.2	0.0	18.4	0.0	1.0	0.1	0.2	0.6	0.0	0.3	0.4	3.4	0.1	0.1	0.1	0.2	0.2
	Wheat gluten	5.5	0.1	0.0	5.7	0.3	0.0	42.2	0.0	1.6	0.2	0.2	0.3	0.1	0.2	0.4	5.9	0.1	0.1	0.1	0.2	0.2
	Wheat bran	1.7	0.0	0.0	1.7	0.1	0.0	4.7	0.0	0.4	0.0	0.0	0.1	0.0	0.1	0.1	0.7	0.0	0.0	0.0	0.0	0.0
	Wheat germ	4.4	0.1	0.0	4.6	0.1	0.0	5.7	0.0	1.1	0.1	0.1	0.1	0.1	0.1	0.1	0.8	0.0	0.1	0.1	0.1	0.1
	Brewer’s spent grain	2.8	0.0	0.0	2.7	0.1	0.0	6.5	0.0	0.5	0.1	0.1	0.1	0.0	0.1	0.1	1.3	0.0	0.1	0.1	0.0	0.1
	Peanut meal	4.5	0.1	0.0	8.6	0.1	0.0	12.7	0.0	1.5	0.1	0.1	0.2	0.1	0.1	0.2	1.1	0.0	0.1	0.1	0.1	0.1
	Pea protein concentrate	6.8	0.2	0.0	14.4	0.1	0.0	19.5	0.0	1.7	0.2	0.2	0.3	0.2	0.1	0.3	1.9	0.1	0.2	0.1	0.1	0.2
	Soy meal	4.9	0.1	0.0	8.4	0.1	0.0	12.0	0.0	1.1	0.1	0.1	0.2	0.1	0.1	0.2	1.4	0.0	0.1	0.1	0.1	0.2
	Green seaweed	1.9	0.0	0.0	2.4	0.0	0.0	1.9	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.0	0.0	0.0
	Red seaweed	2.2	0.0	0.0	3.7	0.0	0.0	3.6	0.0	0.5	0.0	0.1	0.1	0.0	0.1	0.1	0.5	0.0	0.1	0.1	0.0	0.1
	Brown seaweed	1.0	0.0	0.0	2.7	0.0	0.0	1.6	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0
	Green microalgae	9.4	0.1	0.0	7.1	0.0	0.0	8.2	0.0	1.6	0.1	0.1	0.3	0.1	0.2	0.2	1.5	0.0	0.2	0.2	0.1	0.2
	Cyano bacteria	10.2	0.1	0.0	8.7	0.0	0.0	11.4	0.0	1.7	0.1	0.2	0.3	0.1	0.2	0.3	1.4	0.1	0.2	0.2	0.2	0.2
	Pichia pastoris yeast	6.3	0.1	0.0	6.0	0.0	0.0	6.8	0.0	0.9	0.1	0.1	0.2	0.1	0.2	0.3	1.0	0.0	0.1	0.0	0.1	0.1
	Candida utilis yeast	4.4	0.1	0.0	3.0	0.0	0.0	5.1	0.0	0.7	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.1
	Yarrowia lipolytica yeast	6.1	0.0	0.0	4.5	0.1	0.0	5.5	0.0	0.8	0.1	0.1	0.1	0.1	0.1	0.1	0.8	0.0	0.1	0.3	0.2	0.1
	Yeast	10.3	0.1	0.0	9.0	0.1	0.0	15.4	0.0	1.6	0.1	0.2	0.3	0.2	0.2	0.3	1.3	0.0	0.2	0.2	0.0	0.2
	V. natriegens	7.3	0.0	0.0	13.4	0.0	0.0	7.6	0.0	1.4	0.0	0.1	0.2	0.1	0.2	0.2	1.2	0.0	0.1	0.0	0.1	0.2
	E. coli	8.8	0.0	0.0	8.2	0.0	0.0	8.8	0.0	1.6	0.0	0.2	0.3	0.1	0.3	0.2	1.2	0.0	0.2	0.0	0.1	0.2
	G. LC300	9.4	0.0	0.0	11.2	0.0	0.0	9.3	0.0	1.5	0.0	0.2	0.3	0.1	0.3	0.2	1.3	0.0	0.2	0.0	0.1	0.3

Figure 10. Ratio of individual amino acid concentration in hydrolysates and raw materials compared to the FSF4 media. This heat map displays the ratios of individual amino acid concentrations (g AA/g raw material or hydrolysate) for 50 different raw materials and hydrolysates compared to the amino acid concentration (g AA/L of media) in the FSF4 media formulation. A ratio of 1 or greater indicates that 1 g of the material meets or exceeds the concentration in 1 L of FSF4 media. These results underscore the probable need to combine multiple materials and/or hydrolysates to achieve a more balanced and media-compatible amino acid profile suitable for cultivated meat production.

Top hydolysate blend options in grams of dry mass

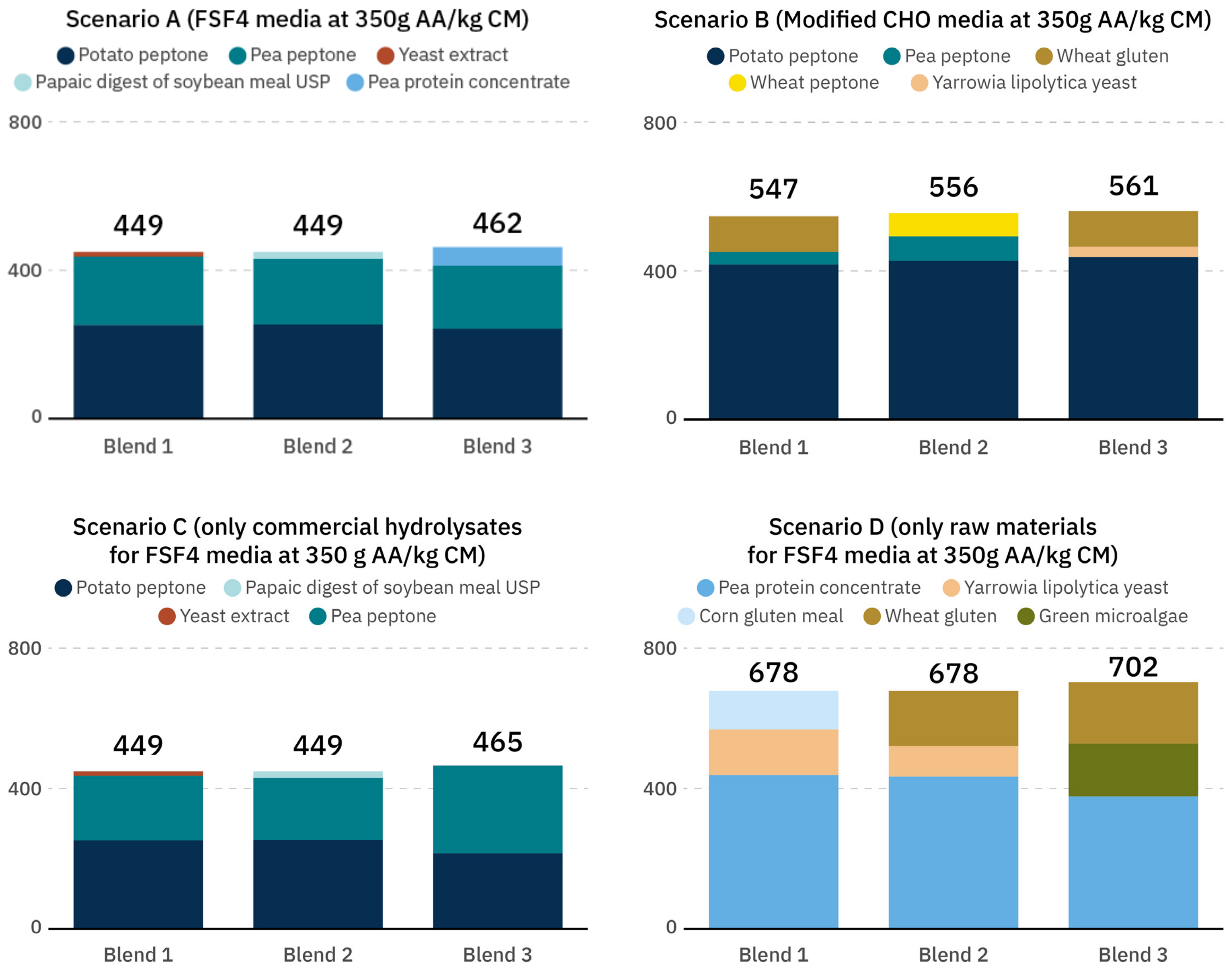


Figure 11. Top raw material or hydrolysate blend options across four scenarios. This figure presents the three top hits for blends across each of the four scenarios described in the Extended Methods (Table A4). Scenario A models the FSF4 media formulation assuming a bioconversion efficiency of 350 g AA/kg CM. Scenario B models the modified CHO media formulation at the same efficiency. Scenario C models the media and bioconversion efficiency of Scenario A, but limits input options to only commercially available peptones, while Scenario D considers only raw materials. Each column represents a blend composed of up to three raw materials or hydrolysates, with the relative contribution of each shown by segment size, allowing for direct comparison of blend composition and diversity across scenarios.

The top candidate blend is shown in **Figure 12**, which visualizes the contribution of pea peptone, potato peptone, and yeast extract to the individual amino acid requirements to produce 1 kg CM using the FSF4 media. Tyrosine, histidine, and tryptophan were the limiting amino acids, with all others being oversupplied (with the exception of the “Spiked AAs” previously noted). Yeast extract displays a “topping up” effect due to ChatGPT finding results that restrict the total mass of material used. In practice, it may be easier to blend just pea and potato peptone, which can also fulfill the amino acid requirements through a slight increase in the total amount of material required (e.g., 449 g for pea/potato/yeast vs. 465 g for pea/potato shown in Scenario C).

Hydrolysate price thresholds

Many studies have discussed the potential of using hydrolysates in media, but few have evaluated the price profiles they would need to achieve to reduce rather than raise media costs. To evaluate the cost competitiveness of hydrolysate-based media, we modeled the maximum allowable price thresholds ($/kg hydrolysate blend) for the 12 blends identified previously in **Figure 11** to determine what a blend’s price would need to be to be competitive with amino acids derived from fermentation (see Extended Methods). The calculations accounted for blends that contained low amounts of arginine and serine (as shown in **Figure 12**), which offset the cost contributions of spiking these two amino acids.

Top hydrolysate blend amino acid profile vs FSF4 requirements for 1 kg CM
(g AA)

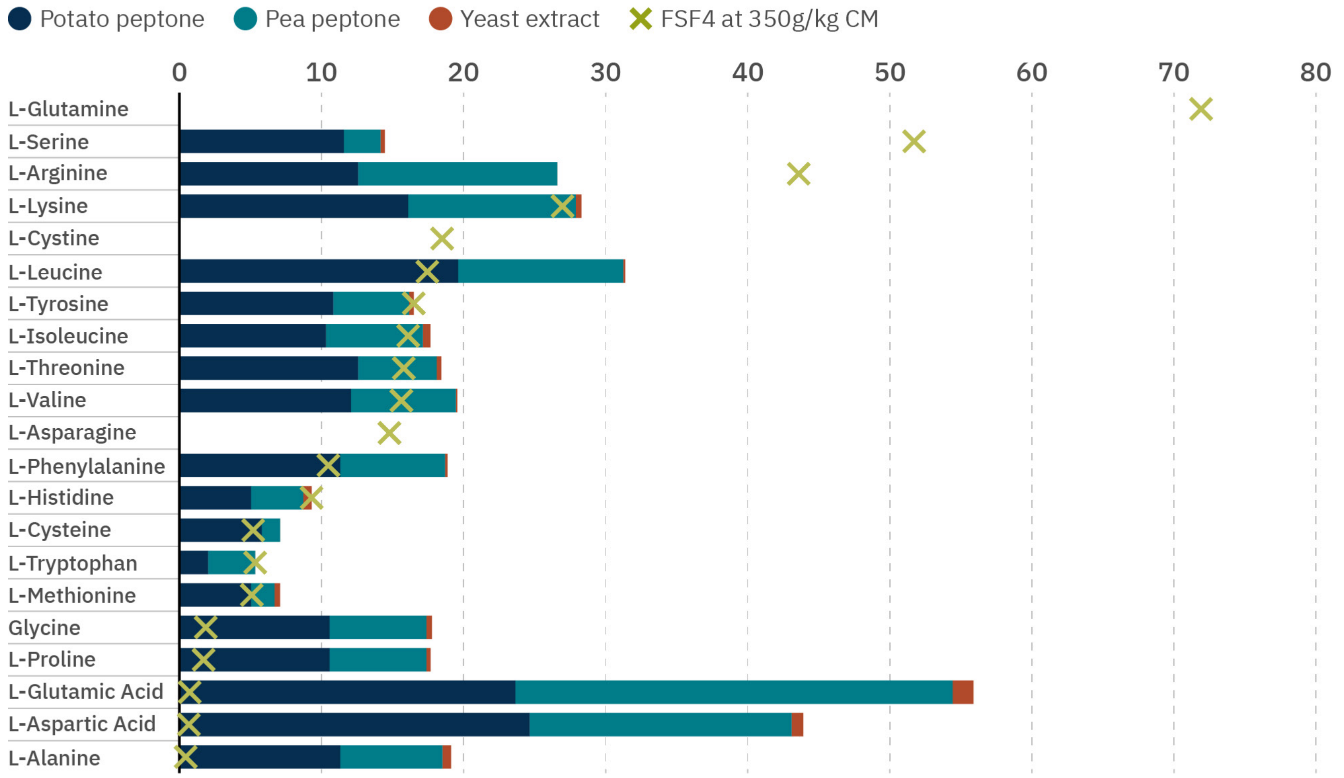


Figure 12. Amino acid contributions of the top candidate blend vs the amino acids needed for 1 kg CM. Here we compared the amino acid contributions of the top hit, composed of potato peptone, pea peptone, and yeast extract, against the estimated amino acids needed to create 1 kg of CM, assuming the FSF4 media formulation is used and 350 g AA/kg CM is required (green Xs). Each individual material’s contribution is depicted within stacked columns, allowing for visualization of how the blend components complement each other to approach the desired formulation.

Furthermore, different media formulations have different amino acid requirements. Accordingly, the blend with the least amount of required dry mass does not necessarily correspond to the blend with the most favorable price profile, as the amount and type of spiked AAs needed can have a significant impact on cost.[5]

Table 3 shows the prices for hydrolysate blends to be competitive with fermentation-derived amino acids under the three pricing scenarios. The blend with the most favorable price profile was composed of potato peptone, pea peptone, and wheat gluten (**Blend B1, Figure 11**). It had the highest permitted price range ($2.79 to $11.27/kg hydrolysate blend) because the modified CHO media formulation contains lower amounts of serine, and the blend is able to fulfill most of the serine needs, offsetting costs associated with spiking it in. All blends in Scenario B had the most favorable price profiles for this same reason. The blend with the least favorable price profile (Blend D1, $1.51 to $7.12) was composed of pea protein concentrate, corn gluten meal, and *Yarrowia lipolytica* yeast. All blends in Scenario D were similarly unfavorable because they required significantly more material, resulting in lower allowable prices per kg of hydrolysate blend.

Table 3. Maximum allowable price ranges for different hydrolysate blends to achieve parity with fermentation-derived amino acids. The lowest and highest values ($1.51–$11.27/kg hydrolysate blend) represents the competitive pricing window for these blends, depending on fermented amino acid pricing.

	Feed-grade price scenario for fermented AAs	**Low food-grade price scenario for fermented AAs**	**High food-grade price scenario for fermented AAs**
Blends	**Price allowance ($/kg hydrolysate blend) to be at parity with a media composed of amino acids derived solely through fermentation**		
A1	$2.02	$4.08	$9.30
A2	$2.03	$4.11	$9.36
A3	$2.00	$4.05	$9.25
B1	$2.79	$5.57	$11.27
B2	$2.73	$5.41	$10.99
B3	$2.73	$5.46	$11.02
C1	$2.02	$4.08	$9.30
C2	$2.03	$4.11	$9.36
C3	$1.95	$3.90	$8.98
D1	$1.51	$3.13	$7.12
D2	$1.55	$3.24	$7.30
D3	$1.52	$3.17	$7.10

---

[5] The highest prices were deemed the most favorable, as it is presumably easier to create a hydrolysis process with a higher price target than a lower one.

The lowest and highest values ($1.51-$11.27/kg hydrolysate blend) represent the competitive pricing window for hydrolysate blends identified in this analysis. Because the results are sensitive to several variables (e.g., bioconversion efficiency assumptions, media formulation, amino acid prices, amount and need for spiked AAs, hydrolysate types and composition), this price range should be viewed as a starting point for practitioners developing hydrolysis processes for cultivated meat. It is important to note that this range should also be viewed as fairly idealistic, as it assumes that all amino acids are bioavailable and that conversion efficiency is at 350 g AA/kg CM, which may be optimistic in the near term. Additional considerations are discussed in the Appendix (**Table A5**).

As a point of comparison, current pricing data acquired during interviews for hydrolysates were limited but varied considerably. While some bulk raw materials can be acquired below this range, added processing costs combined with the low volume and immature hydrolysate market can push current prices (~$5-30/kg hydrolysate per three interviewees) outside this range. Overall, more data are needed to understand the techno-economics of hydrolysate production from different materials.

Taken together, these findings illustrate a promising strategy for identifying candidate hydrolysate blends that could support basal media supplementation or partial amino acid replacement. While none of the 50 hydrolysates and raw materials analyzed individually provided a practical means for complete amino acid coverage, several blend combinations were identified using a constrained optimization approach. The consistency of certain inputs, such as pea and potato peptones in Scenarios A–C, or raw materials like *Chlorella vulgaris* microalgae and *Yarrowia lipolytica* yeast in Scenario D, highlights their potential as starting points for further process optimization and experimental validation. While highly processed peptones may offer nutritional efficiency, they may be more expensive. Raw materials may offer a more affordable and sustainable alternative, but they will still require processing, potentially introducing costs, altering amino acid composition, or releasing inhibitory compounds that could impact cell culture performance. These examples and price ranges should therefore be viewed as a guide rather than definitive solutions. Recommendations for future research are included in the Discussion.

Fermentation-based amino acid production and sourcing for cultivated meat applications

The sections below reflect industry practices and perspectives on fermentation-based amino acid production, purification, and readiness for use in cultivated meat applications. Additionally, we describe the amino acid supply chain architecture. These findings are based on the structured interviews and questionnaires with cultivated meat stakeholders.

All suppliers confirmed microbial fermentation as the core platform for amino acid production. *E. coli* and *C. glutamicum* were described as the dominant strains due to their high productivity and regulatory familiarity. These organisms have been optimized over decades to improve yield and scale up efficiency. Some respondents also mentioned selective use of chemical synthesis, particularly for sulfur-containing amino acids such as cysteine and methionine, due to technical hurdles in fermentation. One supplier uses chemical synthesis specifically for cysteine, citing cost-effectiveness and stability. Another indicated ongoing innovation in enzymatic conversions and hybrid methods for hard-to-produce amino acids.

Cost drivers of fermentation-based amino acids were multifaceted. Per interviewees, sugar feedstocks (e.g., glucose syrup, molasses) and utilities (steam, electricity, water) were consistently cited as major contributors to variable cost, accounting for up to 80% in some cases. Several producers noted that sugar alone accounts for ~50% of variable cost, while utilities contribute ~30%. Additional costs include chemical reagents (e.g., NaOH, H_2SO_4, ammonia), labor, and purification steps. Amino acids like lysine, which have benefited from decades of strain improvement, exhibit high productivity and low cost. In contrast, newer or technically challenging amino acids, such as histidine or cysteine, suffer from lower yields and higher costs even at scale. We refer readers to a recent summary on the techno-economics of fermentation-derived ingredients for additional information (Eastham et al. 2025).

Significant differences exist between feed-, food-, and pharma-grade amino acids due to differing specifications. Feed-grade amino acids (the quality used in livestock feed) are the lowest-cost tier, tolerating reduced purity, less documentation, and color variability (e.g., off-white or yellowish appearance). These are produced with minimal downstream processing and limited microbial contamination controls. Food-grade amino acids require enhanced purity, refined appearance, and tighter controls, and are produced under food GMP conditions. Additional purification steps, such as activated carbon treatment, ion exchange, and filtration, drive higher costs. Some manufacturers do not offer feed-grade products but may supply an intermediate "industrial-grade" tier (~98% purity), which is not manufactured in GMP environments. In these cases, customers are responsible for managing impurity levels and microbial contamination risks during media formulation, a typical procedure for large-scale media suppliers but still unfamiliar territory for emerging cultivated meat companies. Several respondents emphasized that food- and feed-grade production lines must often be physically separated to meet regulatory requirements. One producer noted that feed-grade and food-grade products cannot be manufactured simultaneously on the same production line due to cross-contamination and documentation standards. Taken together, this implies that retrofitting feed-grade production lines would require significant investment and upgrades to meet food-grade specifications.

Endotoxins, produced by gram-negative bacteria such as *E. coli*, are a known consideration for ensuring high-performing cell cultures. One respondent emphasized that even gram-positive strains such as *C. glutamicum* may still carry endotoxins via environmental contamination. Suppliers noted that pharmaceutical-grade amino acids often undergo additional steps, such as ultrafiltration, specifically aimed at achieving extremely low endotoxin levels, whereas food- and feed-grade products typically do not include these targeted steps. However, standard food-grade purification methods, such as activated carbon treatment, ion exchange, crystallization, and spray-drying, can substantially reduce endotoxin content, even though removal is not their primary purpose. For example, one supplier specified endotoxin at no more than 40 endotoxin units (EU/g) for certain food-grade amino acids, a level generally considered tolerable for cell culture, although another interviewee noted uncertainty about what level is truly tolerable for CM applications. Opinions on the regulatory importance of endotoxins were mixed, with some companies indicating that specifications are required, while others reported that regulators and end users did not raise the issue.

Endotoxin levels in feed-grade amino acids may be more variable and, in some cases, high enough to cause concern for media use. One interviewee noted that additional removal can be achieved through ultrafiltration, as well as heat application (e.g., drying, spray-drying) or desiccation (e.g., crystallization), which could potentially be optimized to further reduce endotoxins. Finally, once an input is incorporated into a complete media formulation, endotoxin concentration is significantly diluted. While endotoxins remain a potential challenge highlighted by several interviewees, current food-grade purification practices, coupled with dilution in media, often appear sufficient to keep levels low, though some uncertainty remains over acceptable limits.

Fit-for-purpose “cultivated meat-grade” amino acid specifications

There was broad consensus among amino acid producers, cell culture media suppliers, and cultivated meat companies that the cultivated meat industry would benefit from a clearly defined “cultivated meat–grade” (CM-grade) specification for amino acids. This emerging grade would balance safety, performance, and cost, establishing standards stricter than those for feed applications but more tailored than food and pharmaceutical-grade requirements. Interviewees emphasized that over-specification (i.e., requiring endotoxin levels or documentation practices from pharma) would unnecessarily inflate costs and discourage broader supplier participation. Instead, a CM-grade should be fit-for-purpose, combining functional performance, quality, safety, and regulatory compatibility. Key specifications could be centered around factors affecting food safety and cell growth, such as microbial contamination (i.e., bioburden), heavy metals, residual solvents, aflatoxins, and endotoxins, combined with relaxed thresholds for color and appearance that are often required to meet food-grade standards. Interviewees also proposed CM-grade should aim to ensure traceability, batch consistency, and documented contaminant testing without creating unnecessary barriers. Many interviewees also stressed the importance of transparent manufacturing processes, raw material suitability, and functional performance over rigid purity thresholds. Companies noted that standards may continue to be refined over time, particularly as regulatory frameworks differ by country and application. Such a framework was seen as essential to unlocking scalable, affordable inputs for the cultivated meat sector without compromising product safety or cell culture performance. Additional considerations are included in the Discussion.

Supply chain architecture for cultivated meat applications

The supply chain for fermentation-based amino acids used in cultivated meat is still evolving. It is decentralized and largely shaped by infrastructure originally developed for pharmaceutical and animal feed applications. The current supply chain generally consists of amino acid suppliers, cell culture media companies, and CM companies.

Individual amino acid suppliers tend to manufacture only a subset of the 20+ amino acids that may be used in cultivated meat production. As a result, many different suppliers will be needed to meet future demand. China is the dominant producer and exporter of many amino acids, with additional production hubs in South Korea and South America. While some production occurs in other regions such as Japan, India, the U.S., Europe, and Southeast Asia, these regions tend to rely on imports due to less infrastructure or higher production costs.

Cell culture media companies are critical integrators and distributors along the supply chain. They source amino acids from a patchwork of up to dozens of manufacturers and distributors across the globe.

These amino acids, alongside other media inputs, are imported in bulk and requalified, mixed, and packaged for distribution to CM company end users (**Figure 13**). Cell culture media companies perform extensive supplier due diligence to ensure quality and reliability, and often maintain multiple suppliers for each amino acid for redundancy and competition.[6] Interviewees noted that their competitive advantage is often their supplier network, which enables them to lock in lower prices with suppliers producing high-quality inputs. They also emphasized the importance of quality, consistency, and documentation, with endotoxin levels, heavy metal content, allergen status, and animal-free certification being repeatedly cited as critical specifications when selecting amino acid suppliers.

While some CM companies are considering or have already invested in capabilities for in-house media sourcing and formulation, few currently purchase amino acids directly at industrial scales. Instead, they rely on media companies that purchase in bulk and can formulate and ship custom, pre-mixed powdered media according to the requirements of each customer.[7] Most CM companies avoid in-house media sourcing because it requires considerable investment and overhead to source the dozens of inputs in most media formulations, specialist equipment and personnel to mix and formulate the media, and the establishment of additional quality assurance teams and programs. The layered supply network outlined in **Figure 13** adds complexity and cost to media sourcing for CM companies, but provides reliability, flexibility, and risk mitigation against inventory shortages or regional regulatory issues for end users.

Simplified global supply chain architecture

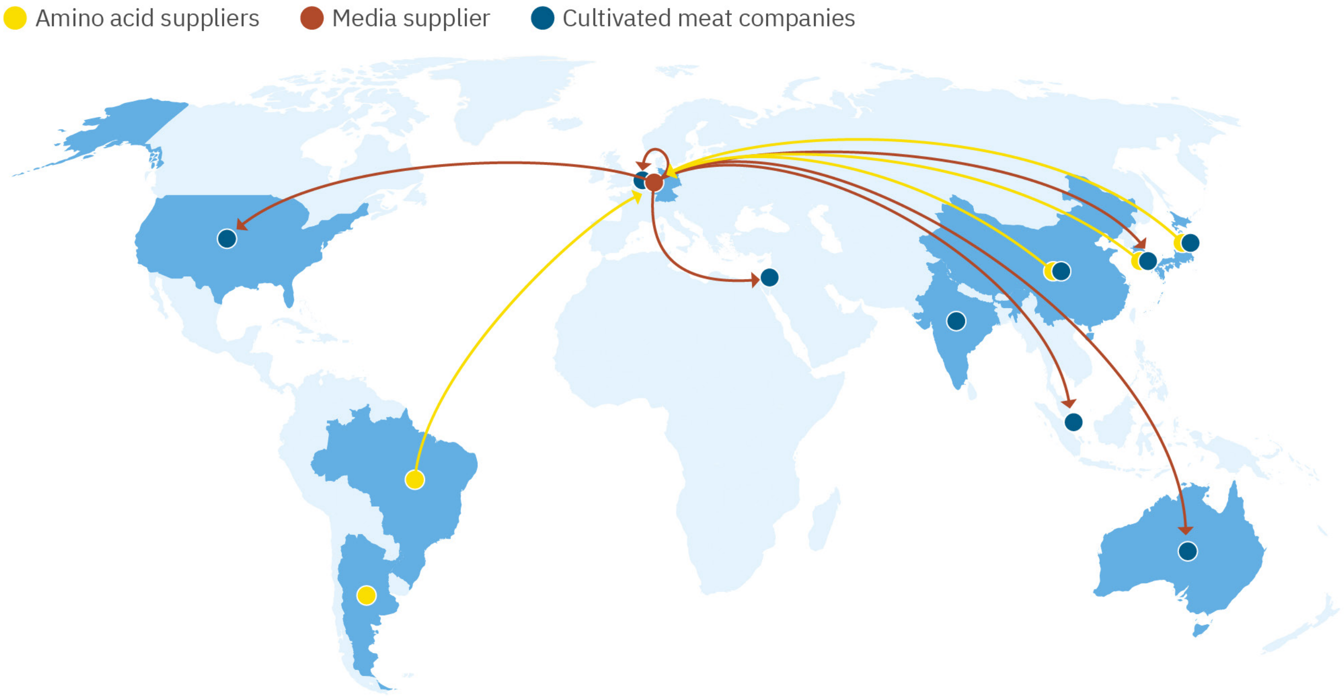


Figure 13. Visualization of the amino acid supply chain for cultivated meat media. In this simplified example, a media supplier sources amino acids from many global suppliers before formulating and shipping media to global cultivated meat customers. In practice, media suppliers will often have localized facilities in several regions to optimize shipping and logistics.

---

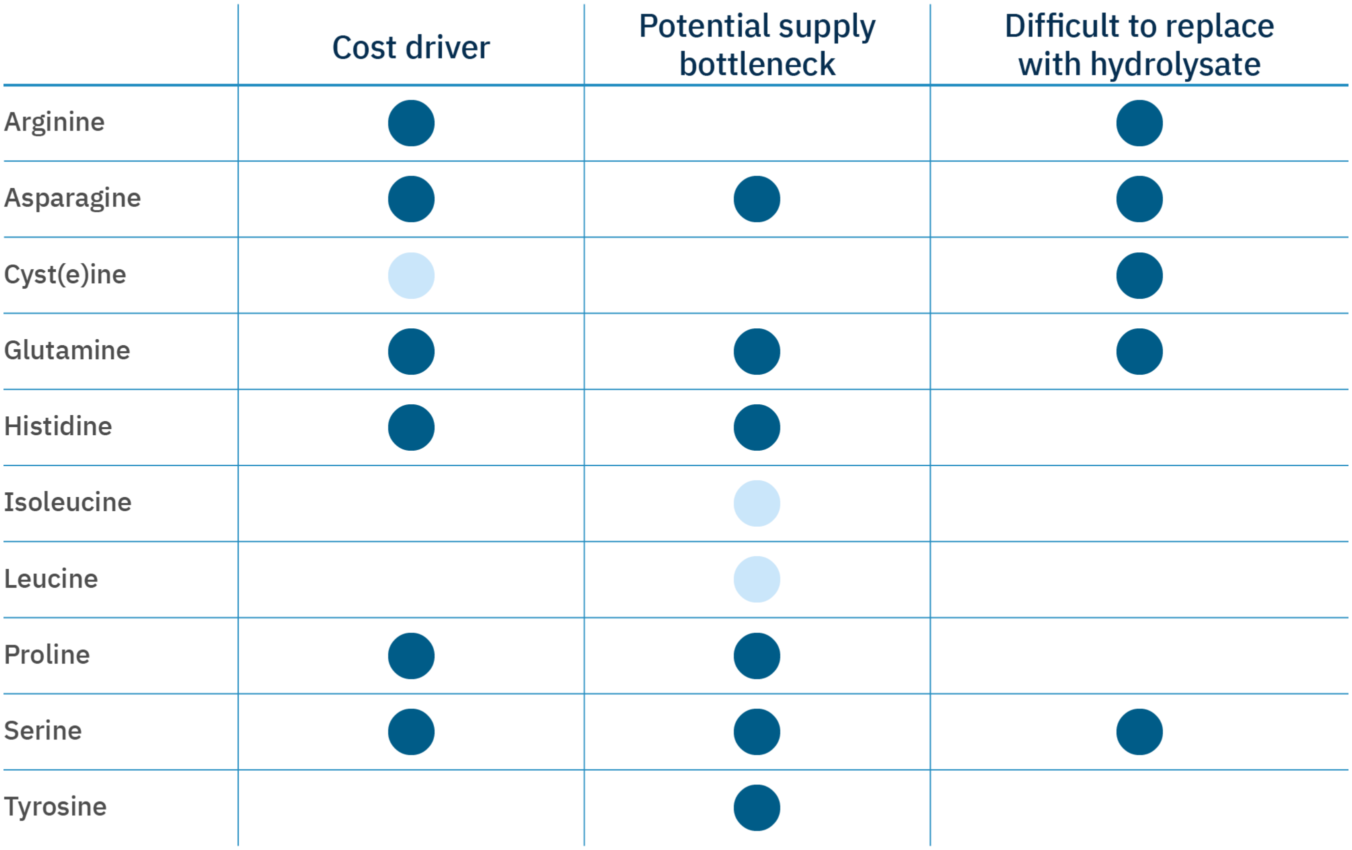
[6] Interviewees noted that while the prices of food-grade amino acids on aggregate supplier sites such as Alibaba were generally representative, they discourage the use of sourcing through aggregate supplier websites due to variability and quality issues.

[7] Media formulations are often held as trade secrets, which underscores the importance of having commercially-relevant formulations like FSF4 made publicly available.

Discussion

High cost and supply-constrained amino acids present new innovation opportunities

Our analysis yielded several new insights into opportunities, challenges, and potential bottlenecks related to the amino acid supply for cultivated meat. **Figure 14** summarizes the key findings, highlighting the amino acids that are currently expensive or in limited supply and difficult to replace using hydrolysates, which indicates they are most likely to remain supplied through fermentation. This nexus highlights the opportunity areas for amino acid innovation and provides direction for researchers and amino acid suppliers to focus their efforts in the coming years. Additional information on each of these amino acids and opportunities for researchers and suppliers can be found in the "High-risk amino acid snapshots" section of the Appendix.



High-risk amino acids

	Cost driver	Potential supply bottleneck	Difficult to replace with hydrolysate
Arginine	●		●
Asparagine	●	●	●
Cyst(e)ine	○		●
Glutamine	●	●	●
Histidine	●	●	
Isoleucine		○	
Leucine		○	
Proline	●	●	
Serine	●	●	●
Tyrosine		●	

Figure 14. Heatmap summary of key results from the analysis, which shows the overlap in amino acids that are cost drivers, in limited supply, and difficult to replace with hydrolysates. Lighter shades indicate lower risk.

Amino acid prices are significantly lower than previously estimated

Amino acids are widely acknowledged as one of the primary cost drivers in cultivated meat media. Early techno-economic assessments, most notably by Humbird, estimated that amino acids could contribute between ~$18-$19/kg CM, a figure that placed them at the center of discussions around economic feasibility for the industry. However, our research has shown that the underlying price assumptions previously used (between $40 and $156/kg AA) were overinflated and more representative of pharmaceutical-grade pricing. Pricing of food-grade amino acids at today's purchase volumes of 25-100 kg tends to span between ~$5 to $75/kg AA, with some price differences being over an order of magnitude less than previously assumed **(Figure 5**).

Lower amino acid prices result in lower estimates for the cost contribution of amino acids to cell culture media and overall cultivated meat production. Over the last few years, it has been commonly cited that $1/L media is a target benchmark necessary to approach cost-competitive cultivated meat. However, the study from which this target was derived was also based on outdated amino acid prices (Negulescu et al. 2023). In support of recent company statements, our analysis shows that commercially-relevant media costs below $0.20/L are quite reasonable (**Figure 6**), and we recommend this as an updated benchmark for researchers and companies to strive for.

Furthermore, several scenarios in our analysis suggest total amino acid costs may contribute less than $5/kg CM. This is a significant decrease from previous estimates of $18-19/kg CM, which accounted for up to half the total cost of cultivated meat production (Humbird 2021). While these calculations exclude all of the other aspects that make up the total cost of production, updated pricing for amino acids suggests that the outlook for cost-competitive cultivated meat is more optimistic than previously believed.

Moving forward, we recommend using the updated price estimates from this study (**Table 1**) in future research characterizing media costs and cultivated meat techno-economics.

Future outlook

Establishing "CM-grade" media inputs to lower costs and streamline the regulatory process

A consistent theme throughout the interviews was the critical role that ingredient grade plays in both the cost and regulatory viability of amino acids for cultivated meat. Currently, pharma-grade amino acids are predominantly used for R&D in academia and early-stage startups. However, the majority of amino acids are already supplied as food-grade to CM companies nearing commercialization, when higher production volumes require bulk purchasing of powdered media. Additionally, several interviewees have begun testing feed-grade amino acids in R&D applications and noted that they often perform equivalently to higher grades in cell culture. However, the use of feed-grade inputs is clouded by concerns around heavy metal content, endotoxin, bioburden (i.e., microbial contamination), batch variability, and inconsistent CoA documentation, issues that can create delays or rejections in regulatory review processes. In some jurisdictions, such as South Korea, explicit requirements for food-grade inputs restrict use of other input types, while in the EU and US, acceptability appears to hinge on prior food-use history and overall safety evidence.

Input grades can be nebulous and standards may vary by jurisdiction. Accordingly, one interviewee noted that they do not even think in terms of "grades" but focus instead on locating suppliers who can provide low-cost inputs that meet the safety and performance profile suitable for cultivated meat. This general concept for the creation of a "cultivated meat-grade" specification was supported by almost every interviewee. This new standard could draw from food- and feed-grade benchmarks but introduce fit-for-purpose criteria such as verified endotoxin thresholds, maximum limits on heavy metals, microbial contamination, and other impurities of concern, animal-origin-free verification, consistent batch documentation and CoA formatting, and harmonization of traceability audits or input swaps during the regulatory review process. For example, there is currently a lack of clarity for CM manufacturers who have an approved product but may want to swap a pharma-grade amino acid (used during initial submission) for a food-grade amino acid used in current production. While some interviewees suggested this may only require a simple notification to the regulator if the Chemical Abstracts Service (CAS) number is unchanged, others suggested that reviewers may raise additional questions about the identity of impurities that could exist in the food-grade version.

Establishing a CM-grade can also be overlaid with safe limits for media inputs (Ong et al. 2025) to promote transparent dialogue with regulators and streamline the approval process, while also unlocking the use of more affordable and widely available amino acid sources, particularly those currently categorized as feed-grade but suitable for cell culture use. Several interviewees noted they have already begun to develop such programs internally and consider this a competitive advantage in offering lower-cost inputs to the cultivated meat sector.

Developing a new standard will require coordinated effort between regulators and the suppliers, media companies, and CM manufacturers that make up the supply chain. These efforts could be additionally supported through public-private consortia, new standards-setting organizations for cultivated meat, and pre-competitive R&D projects that characterize the safety and performance of different materials. Based on the enthusiasm expressed by interviewees, we consider this a key area of focus for the continued development of the future media supply chain. Foregoing such an effort in favor of defaulting to higher-grade inputs could unnecessarily constrain innovation and prevent cost-competitive production at commercial scales.

Recommendations to address challenges:

Cross-sector collaboration to develop “cultivated meat–grade” standards: Establishing fit-for-purpose, standardized criteria for amino acid quality, such as verified endotoxin thresholds, maximum limits on heavy metals, bioburden (i.e., microbial contamination), other impurities of concern, and animal-origin-free verification can streamline documentation and regulatory compliance. Interviewees nearly unanimously supported this effort.

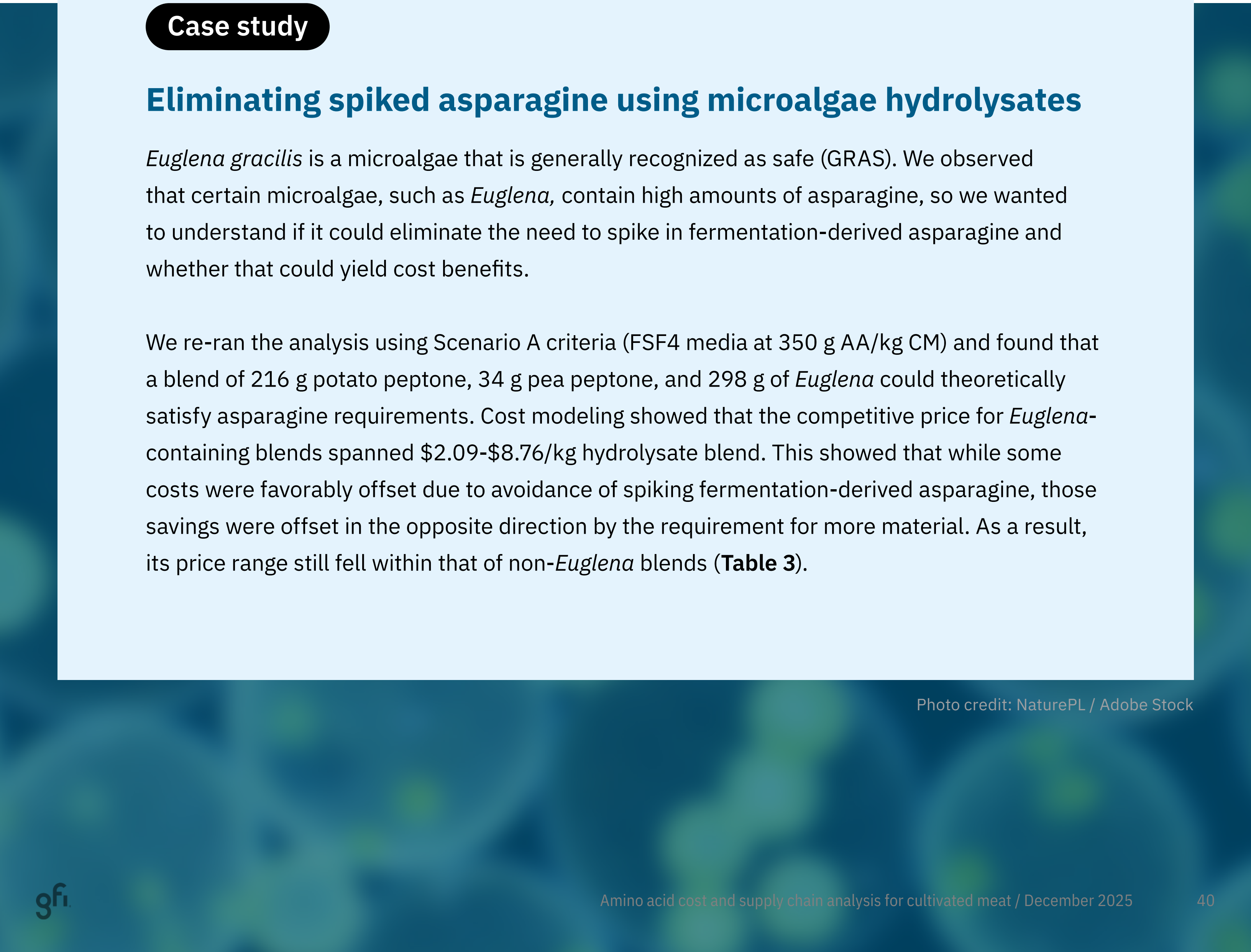
Advancing the use of hydrolysates

When considering a future cultivated meat industry where volumes move beyond the millions of tonnes of production, diversifying the supply of amino acids and other basal media components is likely to be an important long-term goal. As previously discussed, hydrolysates from bulk raw materials may offer numerous advantages in cost, environmental impact, and supply chain simplicity, circularity, and resilience. However, their uptake in commercial production is likely to remain limited until technical challenges are resolved. What steps should be taken to advance the use of hydrolysates?

Our analysis presents a strategy for narrowing the search space for raw materials to match the nutritional requirements of commercially-relevant media formulations and determine which individual amino acids may need to be spiked in. Since most studies exploring hydrolysates are currently performed through trial and error, we recommend using this updated strategy to increase the efficiency of finding and replicating hits in hydrolysate screening pipelines.

It is important to note that the results from this analysis should be viewed as preliminary findings. The dataset currently includes only 50 raw materials or hydrolysates, and several limitations to the approach are noted in **Table A5**. Researchers can build on these initial results by expanding the food-safe materials dataset and developing algorithms that can simultaneously optimize multiple variables such as cost, environmental metrics, dry mass amounts, and AA supplementation to enable a more complete understanding of the tradeoffs at play. For example, the case study below shows how different starting materials could be leveraged to achieve a specific goal, such as eliminating the need to spike in asparagine.

Additionally, the determination of a pricing window ($1.51-$11.27/kg) for hydrolysate blends to be competitive with fully fermentation-derived media provides a valuable starting point for those pursuing hydrolysate research. To our knowledge, these are the first reported target prices for hydrolysates, enabling practitioners to model and develop hydrolysis processes that are designed to be cost-competitive from the beginning. Interviewees indicated that producing hydrolysates in this range is likely feasible, however, more research into the techno-economics of hydrolysate production is needed.



Case study

Eliminating spiked asparagine using microalgae hydrolysates

Euglena gracilis is a microalgae that is generally recognized as safe (GRAS). We observed that certain microalgae, such as *Euglena,* contain high amounts of asparagine, so we wanted to understand if it could eliminate the need to spike in fermentation-derived asparagine and whether that could yield cost benefits.

We re-ran the analysis using Scenario A criteria (FSF4 media at 350 g AA/kg CM) and found that a blend of 216 g potato peptone, 34 g pea peptone, and 298 g of *Euglena* could theoretically satisfy asparagine requirements. Cost modeling showed that the competitive price for *Euglena*-containing blends spanned $2.09-$8.76/kg hydrolysate blend. This showed that while some costs were favorably offset due to avoidance of spiking fermentation-derived asparagine, those savings were offset in the opposite direction by the requirement for more material. As a result, its price range still fell within that of non-*Euglena* blends (**Table 3**).

Photo credit: NaturePL / Adobe Stock

In the near term, screening and experimental validation work will be a priority. However, there are numerous factors outside of our analysis scope that may be important considerations for determining why certain hydrolysates work or fail in validation studies:

- **Defining the goal:** As mentioned in **Table A5** (Extended Methods), our analysis examines hydrolysates solely through the lens of amino acid replacement. In practice, hydrolysates may contain bioactive peptides and other compounds that display the capacity to replace serum, growth factors, antioxidants, and other basal media components. Accordingly, the goal of the study (e.g., growth factor replacement vs. amino acid replacement) should be clearly defined with proper controls to determine the effect of the hydrolysate. Different goals are likely to require different hydrolysis protocols. Additionally, consistent outcome criteria based on growth rate or bioreactor volumetric productivity will be important to ensure commercial relevance and comparability of results across labs and studies. Recent demonstrations imply it is likely that hydrolysates and/or lysates and protein fractions from raw materials gain traction for serum and growth factor replacement before they become viable solutions for basal media components (Dolgin et al. 2025; Stout et al. 2022).
- **Osmolality and solubility:** The top hit in our analysis, a blend of pea peptone, potato peptone, and yeast extract, required 449 g of material to meet the requirements of the FSF4 media formulation, assuming a bioconversion efficiency of 350g AA/kg CM. This scenario assumes approximately 100L of media is used to create 1 kg CM and translates to the equivalent of adding ~4.5g of hydrolysate per liter of media. This would make the hydrolysate second only to glucose (5 g/L) in weight within the FSF4 media formulation. This could consequently increase the osmolality of the media, leading to growth inhibition effects due to osmolality (O'Toole 1997) rather than some inhibitory factor in the hydrolysate. High amounts of material used could also impact solubility, leading to precipitation. Consideration and correction for media osmolality and pH prior to use will be important to eliminate confounding variables and effectively troubleshoot.
- **Scale up:** As experimental validation is performed in larger bioreactors, hydrolysates may also influence foaming rates, media viscosity, and oxygen transfer, requiring adjustments to mixing, feeding, and antifoam protocols. Again, knowledge of these potential effects ahead of time will enable practitioners to proactively design compatible processes and effectively troubleshoot.

Another area that requires a large research effort is the optimization of hydrolysate composition based on specific processes tailored to specific end goals. As mentioned in **Table A5 (Extended Methods)**, a limitation in our analysis is the assumption that amino acid composition in raw materials is unchanged post-hydrolysis or post-processing. In reality, the composition of free amino acids is not only likely to change but also display variability. Solving for batch-to-batch variability and increasing performance predictability will require a large effort over many years that is best accomplished through open, pre-competitive R&D. Researchers should focus efforts on:

Hydrolysis protocols:

- Developing cost-effective hydrolysis protocols that yield predictable compositions. Key variables for optimization include pre-treatments of the raw material (e.g., solvent extraction vs. pressing; milling and filtration steps) and enzyme types and conditions.
- Determining whether hydrolysis protocols can be generalized or will need to be tailored to each specific raw material.

Characterizing composition:

- Determining the nutritional composition (e.g., free amino acids, peptides, carbohydrates, lipids, micronutrients, etc) of different hydrolysates with different hydrolysis and fractionation protocols.
- Developing analytical tools to identify potentially beneficial (e.g., antioxidant, antimicrobial) or harmful compounds or metabolites (e.g., inhibitory tannins, polyphenols, and antinutrients) and developing methods to enhance or remove their presence. This characterization may also ease regulatory evaluation.
- Developing cell-line specific screening tools to test performance across hydrolysate blends.

Cell line adaptation:

Since cells are not typically grown in hydrolysates, they may require adaptation protocols where the hydrolysate is phased in at certain concentrations that get elevated over time. Some cell lines may also tolerate more variance in composition than others.

Generating open datasets:

Making sense of the complex data generated from screening can be assisted through the development of software tools, predictive models, and other AI/ML methods (Isaac et al. 2024). These models can be further refined based on media design and cell type compatibility.

Creating robust sourcing pathways:

If low-cost, scalable, nutrient-rich raw materials are identified as suitable amino acid replacements in cell culture media, large-scale production will be critical. Several promising options we have already identified include pea, potato, yeast, soy, wheat, and algae.

Finally, if performance and variability issues can be solved, techno-economic and life cycle assessments can inform industrialization pathways for hydrolysates, which will need to be compared to existing fermentation methods to further understand supply chain optimization and tradeoffs.

A diversified amino acid supply strategy, combining fermentation with optimized hydrolysates, will likely be important to meeting the sector’s long-term cost and sustainability targets. As cultivated meat moves closer to industrial-scale production, addressing these upstream input challenges will be just as critical as advances in bioreactor design, cell line engineering, or process control. The path to scale will depend not only on scientific breakthroughs but on coordination between manufacturers, regulators, researchers, policymakers, and civil society to build an amino acid supply chain that is resilient, cost-effective, and ready for the demands of a global protein transition.

Recommendations to address challenges:

Researchers can use the information and strategy in this report to narrow the search space for candidate raw materials for amino acid replacement and align hydrolysis protocol development to cost-competitive targets between $1.51-$11.27/kg hydrolysate. Researchers may also wish to expand the food-safe materials dataset and evaluate additional variables that may impact cost or environmental metrics to better understand potential tradeoffs.

Characterization of hydrolysates and validation of their performance is a complex task with many variables. Datasets will need to be accessible and open-access in order to leverage software tools and AI/ML methods that can help make sense of the data.

Ensuring industry readiness to prevent supply bottlenecks

Based on the collective findings from the interviews and analysis, we conclude that the amino acid supply and broader capacity to manufacture cell culture media is not a current bottleneck for the cultivated meat industry. Media companies have long been anticipating the scale up of cultivated meat production and standing ready to serve this new market, and the existing supply of amino acids is adequate for current needs. For example, our interviews suggest that media companies collectively have the capacity to manufacture well over 10,000 MT of CM media annually, whereas the annual commercial production volumes of cultivated meat are currently less than 1,000 MT. However, amino acid suppliers are not yet closely tracking cultivated meat development, and if demand rises suddenly, supply constraints could quickly push up prices for certain amino acids.

Our analysis was performed on the basis of a future cultivated meat industry producing 250 kTA. However, we explicitly do not provide a timeframe for when these volumes are expected to occur, as the data to predict this is limited. Nevertheless, production volumes of cultivated meat could increase quickly. As of November 2025, ten products have been cleared by regulators, and four are currently on the market across the US, Singapore, and Australia, with more on the way.[8] With newly acquired regulatory approvals, multiple cultivated meat manufacturers now have the greenlight to scale up production into the tonnes and beyond. While 250 kTA of production won't happen overnight, it will be increasingly important to have accurate accounting of cultivated meat production such that suppliers can plan ahead to ensure amino acid supply and demand operate in lockstep.

Furthermore, our calculations based on 250 kTA of cultivated meat represent less than 1% of global meat consumption, and amino acid production will need to increase significantly if cultivated meat is to grow to levels that have a meaningful positive impact on the environment, people, and animals. As production volumes for cultivated meat increase beyond the 250 kTA scale, amino acids could become significant supply constraints in the future. As with any new industry, scaling of the supply chain alongside the broader sector will be critical to achieving production milestones. While no critical amino acid is in shortage today, several companies warned that if the cultivated meat sector suddenly demands hundreds of tonnes of an amino acid that currently has a small market (e.g., serine, tyrosine, proline), lead times for scale up (e.g., new or retrofit fermentation capacity) could create supply bottlenecks and price increases if not proactively addressed. As development progresses, suppliers should actively monitor global cultivated meat production and timelines for new facility openings, which could lead to large, sudden increases in amino acid demand.

This chicken-and-egg scenario may be further mitigated through several interventions taken by other industries and mentioned by interviewees:

- **Proactive infrastructure actions:** Governments have an opportunity to further establish global leadership in cultivated meat production by onshoring domestic amino acid production and increasing supply. See "Mitigating geopolitical risks" below for recommendations.
- **Pooled procurement:** Amino acid suppliers expressed caution about investing in new capacity or retrofitting existing infrastructure for food-grade or "CM-grade" inputs until there is more certain, consolidated demand from the cultivated meat sector. Accordingly, the coordinated purchasing for guaranteed, large volume offtake across multiple CM companies and/or media suppliers can create stronger demand signals, improve negotiating power, and help de-risk supplier investment in larger production runs or new infrastructure.

---

[8] Additionally, two cultivated pet food products have been cleared for sale, with one on the market in the U.K.

- **Develop "cultivated meat–grade" standards:** Currently, amino acid suppliers do not necessarily know what specifications are needed for cultivated meat use. Additionally, several media companies indicated that even when purchasing food-grade amino acids, endotoxin levels, trace metal content, and allergen status are inconsistently reported, making regulatory submissions and cross-batch blending more difficult. As previously discussed, developing "CM-grade" standards can help inform the types of documentation, equipment, and downstream purification processes needed to ensure amino acids are consistently safe, high-performing, and cost-effective.
- **Build strategic reserves of high-risk AAs:** Creating strategic stocks and implementing forward contracts for cost- or supply-sensitive amino acids listed in **Figure 14** could help to prevent price and supply volatility as the cultivated meat industry scales.

Recommendations to address challenges:

- Amino acid suppliers should actively monitor global cultivated meat production and proactively plan capacity to meet growing amino acid demand.
- The cultivated meat sector can explore pooled procurement of amino acids to guarantee large volume offtakes to create stronger demand signals that enable supplier resource allocation into expanded capacity. Parallel development of CM-grade standards can ensure the entire supply chain is operating under the same expectations.

Further reducing the cost burden of fermentation-based amino acids

Our analysis has shown that amino acid costs are significantly lower than previously believed. However, this does not imply that a bottom has been reached. In essence, amino acid production is a form of "precision fermentation," and the same priority areas of focus for R&D could unlock further cost reductions for amino acids. These areas broadly include strain, feedstock, and bioprocess optimization, which can each be designed to meet the safety, regulatory, cost, and performance needs of the CM industry. The CM industry will create a new, larger market for higher cost and/or low-volume amino acids such as serine, tyrosine, proline, and histidine, providing a strong incentive for suppliers to compete on lowering costs for these amino acids. For a deeper dive on these topics, we refer the reader to GFI's Science of Fermentation overview and TEA landscape report. Additional recommendations for specific amino acids are included in the "High-risk amino acid snapshots" section of the Appendix.

On the demand side, cultivated meat companies and researchers can pursue cell line and metabolic engineering strategies centered on optimizing feed conversion ratios. This can be accomplished by reducing dependence on glycolysis and increasing the time that cells spend using the more efficient oxidative phosphorylation pathway (Hefzi et al. 2024). In combination with targeted feeding strategies, this can significantly reduce the overall amount of amino acids required, as well as those used in especially high quantities such as glutamine. Finally, the development of minimal media that limits overfed amino acids can also reduce overall cost burdens (Lyra-Leite et al. 2023).

Recommendations to address challenges:

- Amino acid suppliers and researchers can further optimize strains, feedstocks, and bioprocesses operations to lower the unit cost of high-cost amino acids
- Cultivated meat researchers and manufacturers can increase bioconversion efficiency through cell line and metabolic engineering strategies and lower the overall cost burden by developing minimal media.

Closing data gaps

Although we were able to thoroughly analyze amino acid costs and production volumes by triangulating insights from interviews and the public literature, closing certain data gaps can better refine future analysis of media components.

- **Bioconversion efficiency**: As mentioned in **Table A1 (Extended Methods)**, the range of bioconversion efficiency scenarios of 200-650 gAA/kg CM is still fairly broad. Our analysis showed that amino acid costs are more sensitive to assumptions for efficiency compared to media composition, highlighting the importance of this metric (**Figure 9**). Additionally, metabolic efficiency has been highlighted in CM TEAs as a prerequisite for cost-competitive cultivated meat. To refine this assumption over time, more empirical data from commercially-relevant bioprocesses are needed for the bioconversion of key substrates (e.g., glucose, glutamine, and other amino acids). These data should be reported on a dry cell mass basis to ensure that variance in water composition is eliminated. They can then be translated into estimates for the total feed conversion ratio for cultivated meat, which thus far has been based on models rather than empirical findings. The importance of these data cannot be understated. Every key metric for the industry — from cost to bioreactor volumetric productivity to environmental impact — is strongly influenced by the underlying feed conversion ratio.
- **Media formulations:** Acquisition of the FSF4 media formulation was critical to the execution of this analysis. Additionally, we aimed to provide analysis of media formulation variation through the inclusion of the modified CHO media. However, future analyses can be refined by having access to additional commercially-relevant media formulations, including differentiation media. Composting of IP, as done with SciFi's assets, offers a promising route to achieve this. Alternatively, companies may opt to publish patents or papers that contain descriptive information on media formulations (Moutsatsou et al. 2021; Pasitka et al. 2024).
- **Amino acid production volumes:** While we were able to compile estimates for annual production of amino acids through interviews and public information (**Table 2**), many interviewees stated that these data are generally opaque and considered lower quality. The true production volume of most amino acids suitable for cultivated meat is not currently known, and improved data will be necessary to continually refine which amino acids may be bottlenecked in supply.

Recommendations to address challenges:

- Researchers and cultivated meat manufacturers should publish empirical data from commercially-relevant bioprocesses to determine the feed conversion ratio of cultivated meat and key substrates such as glucose, glutamine, and other amino acids.
- Researchers and cultivated meat manufacturers can refine future analyses by publishing more commercially-relevant media formulations. Nonprofit entities can acquire and compost IP from startups to make the assets open-access.
- Amino acid suppliers and researchers can collaborate to create refined and consolidated databases for amino acid production volumes that are suitable for cultivated meat.

Addressing environmental impact implications

Our research has concluded that in the short term, the cultivated meat industry will likely continue to rely heavily on fermentation-derived amino acids. One recent study assumed that pharma-grade inputs, including amino acids, would be required for cultivated meat production, resulting in elevated environmental impacts compared to previous reports (Risner et al. 2025). This study has since been refuted, and the interviews during this report decisively indicated that food-grade amino acids, supported by existing supply chains, are already being used throughout the industry. Not only are these inputs well-characterized and familiar to regulators, but they are also more cost-effective than previously assumed. However, these findings still have implications for evaluating the environmental impact of cultivated meat.

One well-cited life cycle assessment (LCA) assumed that 75% of amino acids would be supplied by soy hydrolysates by the year 2030 (Sinke et al. 2023)[9], which our analysis reveals is unlikely to hold. Other LCAs have identified amino acids as a key driver of the environmental impact of media production (Tuomisto, Allan, and Ellis 2022), and thus sourcing amino acids solely through individual fermentation processes may elevate total energy use, land required for fermentation feedstocks, and water use upstream in the supply chain. Calculating the environmental impact of media is generally limited by the lack of updated inventory data in LCA databases (Nikkhah et al. 2024). Most studies reference environmental impact data from a 2010 report on feed-grade lysine, methionine, and threonine production, which is then broadly applied to overall amino acid production (Marinussen and Kool 2010).

Moving forward, LCA practitioners should collaborate with amino acid suppliers to create updated inventory data for the production of food- and feed-grade amino acids and other media inputs produced via fermentation. Measurement of real-world amino acid production rather than lab-scale proxies will be critical for accuracy. Future LCAs can also use the FSF4 media formulation and bioconversion efficiency scenarios in this report when establishing mass balances to ensure commercial relevance. The near-term reliance on amino acids from fermentation reinforces the importance of using renewable energy at cultivated meat facilities and throughout the supply chain to achieve sustainable production (Sinke et al. 2023). Encouragingly, amino acid suppliers noted they are actively implementing renewables to achieve their own environmental, social and governance (ESG) goals.

---

[9] This study was funded by GFI.

Recommendations to address challenges:

- Researchers investigating the environmental impact of cultivated meat should assume that amino acids will be supplied primarily by fermentation processes. Because environmental impact data for amino acid production is outdated, researchers and suppliers should collaborate to generate updated inventory data for real-world, food- and feed-grade amino acid production.
- Suppliers should incorporate renewable energy into their production facilities to lower the environmental impact of production.

Mitigating geopolitical risks

Much of the current production capacity for food- and feed-grade amino acids resides in China, with secondary hubs in South Korea and South America. This regional concentration exposes the sector to geopolitical risk, logistical delays, and trade volatility. Interviewees noted that the 2025 U.S. tariffs have already presented challenges. From a national security perspective, governments have an opportunity to further establish global leadership in cultivated meat production. They can incentivize domestic amino acid manufacturing by de-risking CapEx burden through grants, tax incentives, and low-interest loan programs. Onshoring amino acid manufacturing can reduce the dependence and risk of relying on concentrated international supply chains while creating new jobs and economic opportunities to leverage local biomass and feedstocks for amino acid fermentation. Lastly, governments can consider creating strategic reserves for key amino acids or other media inputs that are also important for human and animal nutrition. These actions can collectively mitigate external risk factors that could affect the success of the entire industry while encouraging competition in media input and fermentation feedstock innovation that lowers costs and increases supply chain resilience.

Recommendations to address challenges:

Policymakers and governments should incentivize domestic amino acid manufacturing through grants, tax incentives, and low-interest loan programs. They can also consider creating strategic stocks and implementing forward contracts for cost- or supply-sensitive amino acids listed in **Figure 14** to prevent price and supply volatility as the cultivated meat industry scales.

Photo credit: Sergey Ryzhov / Adobe Stock

Conclusion

Our analysis demonstrates that the economics of amino acid production will be a decisive factor in unlocking the full potential of cultivated meat. While technical feasibility has been established across multiple production platforms, realizing cost-competitive supply at scale will require targeted innovation, sustained investment, and close alignment between industry, researchers, and policymakers. By integrating detailed cost modeling with real-world perspectives from producers and early adopters, this work highlights the challenges and the credible pathways toward solutions. The cultivated meat field now stands at a pivotal juncture: the strategies chosen today to advance amino acid manufacturing, through process optimization, new biotechnological routes, and collaborative infrastructure, will shape the pace and equity of future market growth. Ensuring that amino acid production is efficient, affordable, and resilient is not only critical for commercial viability but also for fulfilling the broader promise of cultivated meat as a sustainable, secure, and scalable contributor to the global protein supply.

Acknowledgments

This analysis would not have been possible without the generous contributions of our interviewees who shared their time, information, data, and insights. We extend our sincere appreciation to all who participated. The following list includes those individuals who consented to be named and does not encompass those who contributed anonymously.

- **Louis Cheung**, JS Biosciences Co, Ltd
- **Aslak Heuser C. Christiansen**, consultant
- **Luke Grocholl**, MilliporeSigma
- **Yuki Hanyu**, PhD, Integriculture
- **Appachu Kodira**, JS Biosciences/KCell
- **Rick Kwekkeboom**, Innovation manager, Meatable
- **Dr. Neta Lavon**, Co-Founder & Chief Technology Officer, Aleph Farms
- **Dr. Ayelet Maor-Shoshani**, Senior Director, Cell Line and Media Development, Aleph Farms
- **Hyoungsouk Myoung**, BIO Business Division, Daesang Corporation
- **Dean Paes**, PhD, Mosa Meat
- **Jill Schriewer**, consultant, WildBio
- **Ruben Smouter**, Strategy manager, Meatable
- **Panagiotis Vlachogiannis**, Business Development and Supply Chain Associate, Nutreco
- **Patrick Westfall**, VP, Research & Development, Bond Pet Foods
- **Mark Whittaker**, President, Scientific Research Consortium, Inc, DBA
- **Susanne Wiegel**, PhD, Strategic Advisor Cellular Agriculture, Biotech, and Life Sciences
- **The Ajinomoto Group**

References

1. Amirvaresi, Arian, and Reza Ovissipour. 2024. "Assessment of Plant- and Microbial-Derived Protein Hydrolysates as Sustainable for Fetal Bovine Serum in Seafood Cell Culture Media." *Future Foods: A Dedicated Journal for Sustainability in Food Science*, no. 100443 (August), 100443.
2. Charteris, Charlotte, and Johannes le Coutre. 2025. "Cultivated Meat Meets Upcycling: Unlocking the Potential of Agricultural Side-Streams." *Future Foods: A Dedicated Journal for Sustainability in Food Science*, no. 100726 (July), 100726.
3. D'Este, Martina, Merlin Alvarado-Morales, and Irini Angelidaki. 2018. "Amino Acids Production Focusing on Fermentation Technologies - A Review." *Biotechnology Advances* 36 (1): 14–25.
4. Dolgin, James, Damayanti Chakravarty, Sean F. Sullivan, Yiming Cai, Taehwan Lim, Pomaikaimaikalani Yamaguchi, Joseph E. Balkan, et al. 2025. "Microbial Lysates as Low-Cost Serum Replacements in Cellular Agriculture Media Formulation." *Food Research International (Ottawa, Ont.)* 201 (115633): 115633.
5. Eastham, L., Panescu, P., Costa, S., Bess, A., Quoc Le, B., Radovanović, V., Mijušković, V. 2023. "Cultivating Alternative Proteins from Commodity Crop Sidestreams." The Good Food Institute. https://gfi.org/wp-content/uploads/2024/02/Sidestreams-analysis.pdf.
6. Eastham, E., McKee, A., Bess, A., Leman, A. 2025. "Driving to Cost Parity: Insights and Recommendations from a Meta-Analysis of Techno-Economic Data for Fermentation Derived Ingredients." The Good Food Institute. https://doi.org/10.62468/trxj5734
7. "FDA Inventory for Human Food Made with Cultured Animal Cells (Believer Meats)." 2025. Accessed August 26, 2025. https://www.hfpappexternal.fda.gov/scripts/fdcc/index.cfm?set=AnimalCellCultureFoods&id=039.
8. Haraguchi, Yuji, Yuta Okamoto, Toru Asahi, and Tatsuya Shimizu. 2025. "Nitrogenous Fertilizer-free Microalgal Culture Using Nitrogen-fixing Cyanobacteria-derived Extracts for Sustainable Food Production." *Phycological Research* 73 (2): 60–69.
9. Hefzi, Hooman, Iván Martínez-Monge, Igor Marin de Mas, Nicholas Luke Cowie, Alejandro Gomez Toledo, Soo Min Noh, Karen Julie la Cour Karottki, et al. 2024. "Multiplex Genome Editing Eliminates the Warburg Effect without Impacting Growth Rate in Mammalian Cells." *Bioengineering*. bioRxiv. https://www.biorxiv.org/content/10.1101/2024.08.02.606284v1.full.pdf.
10. Hubalek, S., J. Melke, P. Pawlica, M. J. Post, and P. Moutsatsou. 2023. "Non-Ammoniagenic Proliferation and Differentiation Media for Cultivated Adipose Tissue." *Frontiers in Bioengineering and Biotechnology* 11 (July):1202165.
11. Humbird, David. 2021. "Scale-up Economics for Cultured Meat." *Biotechnology and Bioengineering* 118 (8): 3239–50.
12. Isaac, Kathy Sharon, Michelle Combe, Greg Potter, and Stanislav Sokolenko. 2024. "Machine Learning Tools for Peptide Bioactivity Evaluation - Implications for Cell Culture Media Optimization and the Broader Cultivated Meat Industry." *Current Research in Food Science* 9 (100842): 100842.
13. Jiaqi Mi, Hui Si Audrey Koh, Vinayaka Srinivas, William R. Birch, Weibiao Zhou. 2025. "Towards Affordable Cultivated Meat: The Potential of Plant Protein Hydrolysates." *Trends in Food Science & Technology*, July, 105178.
14. Kossmann, Hanno, Thorsten Moess, and Peter Breunig. 2025. "The Climate Impact and Land Use of Cultivated Meat: Evaluating Agricultural Feedstock Production." *PloS One* 20 (1): e0316480.

15. Kulis-Horn, Robert K., Marcus Persicke, and Jörn Kalinowski. 2014. "Histidine Biosynthesis, Its Regulation and Biotechnological Application in Corynebacterium *Glutamicum*: Histidine inC. *Glutamicum*." *Microbial Biotechnology* 7 (1): 5–25.
16. Li, Guohua, Qingyang Xu, Haibo Xiong, Yunpeng Liu, Yufu Zhang, Zhichao Chen, and Ning Chen. 2021. "Improving the L-Tyrosine Production with Application of Repeated Batch Fermentation Technology Based on a Novel Centrifuge Bioreactor." *Food and Bioproducts Processing* 126 (March):3–11.
17. Lohr, Verena, Oliver Hädicke, Yvonne Genzel, Ingo Jordan, Heino Büntemeyer, Steffen Klamt, and Udo Reichl. 2014. "The Avian Cell Line AGE1. CR.pIX Characterized by Metabolic Flux Analysis." *BMC Biotechnology* 14 (1): 72.
18. Lyra-Leite, Davi M., Raymond R. Copley, Phillip P. Freeman, Praeploy Pongpamorn, Disheet Shah, Donald E. McKenna, Brian Lenny, et al. 2023. "Nutritional Requirements of Human Induced Pluripotent Stem Cells." *Stem Cell Reports* 18 (6): 1371–87.
19. Marinussen, M., and A. Kool. 2010. "Environmental Impacts of Synthetic Amino Acid Production." Blonk Sustainability. https://website-production-s3bucket-1nevfd7531z8u.s3.eu-west-1.amazonaws.com/public/website/download/f0e6feeb-d39c-45d2-af25-f94d1de9e074/amino-acids.pdf.
20. Moutsatsou, Panagiota, Helder Cruz, Iva Klevernic, Anna Kolkmann, and Anon Van Essen. 2021. Serum-free medium for culturing a bovine progenitor cell. WIPO 2021158103:A1. *World Patent*, filed February 3, 2021, and issued August 12, 2021. https://patentimages.storage.googleapis.com/10/2d/5b/e1ddc6bf916e15/WO2021158103A1.pdf.
21. Negulescu, Patrick G., Derrick Risner, Edward S. Spang, Daniel Sumner, David Block, Somen Nandi, and Karen A. McDonald. 2023. "Techno-Economic Modeling and Assessment of Cultivated Meat: Impact of Production Bioreactor Scale." *Biotechnology and Bioengineering* 120 (4): 1055–67.
22. Nikkhah, Amin, Kirsten Trinidad, David L. Kaplan, and Nicole Tichenor Blackstone. 2024. "Life Cycle Assessment of Beefy-9 and Beefy-R Serum-Free Culture Media for Cell-Cultivated Beef Production." *Sustainable Production and Consumption* 50 (July):168–76.
23. Ong, Kimberly, Kora Kukk, Dean Powell, Wei Ning Chen, Samuel Goh, and Jo Anne Shatkin. 2025. "Development of a Safety-Assessed Media Ingredient (SAMI) Framework for Streamlined Safety Assessment of Cultivated Meat and Seafood Products." *Preprints*. https://doi.org/10.20944/preprints202503.0374.v1.
24. O'Toole, Angela. 1997. "An Investigation into Factors That Cause Inhibition of the Growth of Animal Cells in Vitro." Accessed October 30, 2024. https://doras.dcu.ie/19265/1/Angela_O'Toole_20130718083840.pdf.
25. Pasitka, Laura, Guy Wissotsky, Muneef Ayyash, Nir Yarza, Gal Rosoff, Revital Kaminker, and Yaakov Nahmias. 2024. "Empirical Economic Analysis Shows Cost-Effective Continuous Manufacturing of Cultivated Chicken Using Animal-Free Medium." *Nature Food* 5 (8): 693–702.
26. Patriarca, Eduardo J., Federica Cermola, Cristina D'Aniello, Annalisa Fico, Ombretta Guardiola, Dario De Cesare, and Gabriella Minchiotti. 2021. "The Multifaceted Roles of Proline in Cell Behavior." *Frontiers in Cell and Developmental Biology* 9 (August):728576.
27. Pavlova, Natalya N., Sheng Hui, Jonathan M. Ghergurovich, Jing Fan, Andrew M. Intlekofer, Richard M. White, Joshua D. Rabinowitz, Craig B. Thompson, and Ji Zhang. 2018. "As Extracellular Glutamine Levels Decline, Asparagine Becomes an Essential Amino Acid." *Cell Metabolism* 27 (2): 428–38.e5.
28. Risner, Derrick, Patrick Negulescu, Yoonbin Kim, Cuong Nguyen, Justin B. Siegel, and Edward S. Spang. 2025. "Environmental Impacts of Cultured Meat: A Cradle-to-Gate Life Cycle Assessment." *ACS Food Science & Technology* 5 (1): 61–74.

29. Schwentner, Andreas, André Feith, Eugenia Münch, Judith Stiefelmaier, Ira Lauer, Lorenzo Favilli, Christoph Massner, et al. 2019. "Modular Systems Metabolic Engineering Enables Balancing of Relevant Pathways for L-Histidine Production with *Corynebacterium Glutamicum*." *Biotechnology for Biofuels* 12 (1): 65.
30. Sinke, Pelle, Elliot Swartz, Hermes Sanctorum, Coen van der Giesen, and Ingrid Odegard. 2023. "Ex-Ante Life Cycle Assessment of Commercial-Scale Cultivated Meat Production in 2030." *International Journal of Life Cycle Assessment* 28 (3): 234–54.
31. Stout, Andrew, Addison Mirliani, John Yuen, Eugene White, and David L. Kaplan. 2022. "Simple and Effective Serum-Free Medium for Sustained Expansion of Bovine Satellite Cells for Cell Cultured Meat." *Communications Biology*, June, 2021.05.28.446057.
32. Sun, Tao, Wee Chiew Kwok, Koon Jiew Chua, Tat-Ming Lo, Jason Potter, Wen Shan Yew, Jonathan D. Chesnut, In Young Hwang, and Matthew Wook Chang. 2020. "Development of a Proline-Based Selection System for Reliable Genetic Engineering in Chinese Hamster Ovary Cells." *ACS Synthetic Biology* 9 (7): 1864–72.
33. Swartz, E., Ravi, A., Reeber, A., Levink, J., Huang, T., Smith, B. 2023. "Anticipated Growth Factor and Recombinant Protein Costs and Volumes Necessary for Cost-Competitive Cultivated Meat." The Good Food Institute. https://gfi.org/wp-content/uploads/2023/01/GFI-report_Anticipated-growth-factor-and-recombinant-protein-costs-and-volumes-necessary-for-cost-competitive-cultivated-meat_2023-1.pdf.
34. Tuomisto, Hanna L., Scott J. Allan, and Marianne J. Ellis. 2022. "Prospective Life Cycle Assessment of a Bioprocess Design for Cultured Meat Production in Hollow Fiber Bioreactors." *The Science of the Total Environment* 851 (Pt 1): 158051.
35. Tuomisto, Hanna L., and M. Joost Teixeira de Mattos. 2011. "Environmental Impacts of Cultured Meat Production." *Environmental Science & Technology* 45 (14): 6117–23.
36. Utagawa, Takashi. 2004. "Production of Arginine by Fermentation." *The Journal of Nutrition* 134 (10 Suppl): 2854S – 2857S; discussion 2895S.
37. Valle, D., S. J. Downing, S. C. Harris, and J. M. Phang. 1973. "Proline Biosynthesis: Multiple Defects in Chinese Hamster Ovary Cells." *Biochemical and Biophysical Research Communications* 53 (4): 1130–36.
38. Vergeer, R., Sinke, P., Odegard, I. 2021. "TEA of Cultivated Meat: Future Projections for Different Scenarios." CE Delft.
39. Wu, Qi, Xinyue Chen, Juanjuan Li, and Shengrong Sun. 2020. "Serine and Metabolism Regulation: A Novel Mechanism in Antitumor Immunity and Senescence." *Aging and Disease* 11 (6): 1640–53.
40. Yamanaka, Kumiko, Yuji Haraguchi, Hironobu Takahashi, Ikko Kawashima, and Tatsuya Shimizu. 2023. "Development of Serum-Free and Grain-Derived-Nutrient-Free Medium Using Microalga-Derived Nutrients and Mammalian Cell-Secreted Growth Factors for Sustainable Cultured Meat Production." *Scientific Reports* 13 (1): 498.
41. 胡辉, 李军, and 翁志兵. 2014. Serum-free protein-free culture medium supporting CHO (Chinese Hamster Ovary Cell) high density suspension culture. CN:104073463:A. *Patent*, filed March 29, 2013, and issued October 1, 2014. https://patentimages.storage.googleapis.com/ff/8d/f9/ea926e08449a0f/CN104073463A.pdf.

Appendix

High-risk amino acid snapshots

The amino acid snapshots below are presented in the order of their importance for amino acid suppliers and cultivated meat researchers to focus their efforts.

- L-Serine
- L-Glutamine
- L-Asparagine
- L-Histidine
- L-Proline
- L-Arginine
- L-tyrosine

Lower-risk amino acids

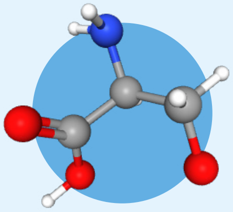
In addition to those above, L-isoleucine and L-leucine were flagged by at least one interviewee as amino acids potentially at risk of a supply bottleneck due to high inclusion rates and a limited number of suppliers. With each amino acid having estimated production volumes in the low thousands of tonnes per year, the projected demands of upwards of 12,300 MT/year to meet 250 kTA CM production could pose significant supply risks.

However, each of these amino acids is used in relatively low quantities in media and are suitable candidates for substitution via hydrolysates, making them lower risk compared to others discussed.

Lastly, L-cyst(e)ine, L-tryptophan, and L-methionine are worth noting. Cyst(e)ine was mentioned most frequently in interviews, with many describing it as inherently challenging to produce. Its instability during manufacturing requires specialized equipment and processes, and fermentation is difficult because of its sulfur content, which is toxic to microbes. Despite these challenges and its high inclusion rate in some media formulations, current global production is over 11,000 MT/year (not accounting for L-cystine production, which was uncertain), above or on par with the ~700–11,000 MT projected for cultivated meat at 250 kTA CM scale.

Similarly, tryptophan was raised as a potential issue due to the complexity of its manufacturing process and the safety considerations posed by potential impurities in food-grade processes. In practice, though, global production is approximately 90,000 MT/year, vastly exceeding the ~750–2,500 MT projected for cultivated meat at a 250 kTA scale.

Finally, methionine is produced for animal feed as D,L-methionine, which may not be suitable for cell culture. Accordingly, production of L-methionine, which is complex due to its sulfur content, may also be an at-risk amino acid. Our analysis was unable to identify current production volumes of pure L-methionine.



L-Serine

Serine was the highest amino acid cost contributor to media

About

Serine is a non-essential amino acid, but it plays a central role in cell metabolism. It is required for protein synthesis and is a precursor in one-carbon metabolism, feeding into nucleotide synthesis and the production of NADPH, NADH, and ATP. Rapidly dividing cells consume serine to support proliferation and fuel nucleotide production; supplying serine in media ensures cells have ample building blocks for these pathways (Wu et al., 2020). Accordingly, serine often has high inclusion rates in media.

Opportunities

Historically, the main manufacturing process uses microbial conversion of glycine (with formaldehyde) into serine. This route is economically inefficient because glycine is a significantly more expensive feedstock than glucose, leading to a high production cost for serine.

Scaling up serine production and investing in further innovation (e.g., in feedstock sources) to drive down costs will be a priority opportunity area for amino acid suppliers to meet the needs of the cultivated meat sector.

☑ Cost driver

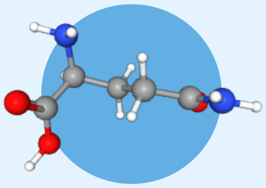
- Serine had estimated food-grade prices of $30-50/kg, second only to histidine.
- Its high price and relatively high usage rates make it the highest cost contributor (16-38% of amino acid costs) in media, depending on the formulation.

☑ Potential supply bottleneck

- Serine has few large-volume applications and consequently only ~400 MT is produced per year.
- Projected serine demand was ~7,400-25,000 MT/yr, far higher than current global production.
- Two interviewees flagged serine as high-risk.

☑ Difficult to replace with hydrolysates

- Hydrolysates can partially supply serine; however, achieving sufficient levels to meet demand will be difficult.
- Serine is likely to remain predominantly supplied by fermentation.



L-Glutamine

Glutamine is the highest contributor to amino acid mass in media

About

Glutamine is one of the most crucial amino acids in cell culture, where it serves as a primary fuel and nitrogen donor for proliferating cells. Glutamine is readily transported into cells, supporting the synthesis of proteins, fats, and nucleotides, making it a major contributor to cellular biomass. It also supports the tricarboxylic acid cycle through anaplerosis (replenishing TCA cycle intermediates) and can serve as an energy source when glucose is insufficient. Because rapidly growing cells consume glutamine at very high rates, media typically contain glutamine at concentrations several-fold higher than any other amino acid.

Opportunities

Glutamine is chemically unstable and degrades into ammonia and pyroglutamate over time at physiological pH. As a result, it is frequently supplemented or used in stabilized dipeptide forms, such as alanyl-glutamine (GlutaMAX).

Opportunities exist to reduce overall glutamine use by utilizing TCA cycle intermediates such as α-ketoglutarate as substrates (Hubalek, 2023), and researchers can examine the potential cost tradeoffs of this approach. Suppliers can support the cultivated meat industry by scaling up production volumes of L-glutamine and lowering the manufacturing cost of α-ketoglutarate and stabilized glutamine sources.

☑ Cost driver

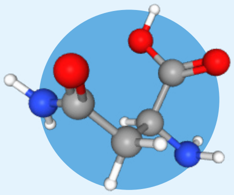
- Glutamine had estimated food-grade prices of $7-16/kg.
- Its cost contribution ranged from 12-17% in FSF4 media, but only 2-3% in modified CHO media, which relies more heavily on asparagine.
- Glutamine's cost contribution is expected to be high, as it can make up 20% or more of amino acid mass in media.

☑ Potential supply bottleneck

- Glutamine production is ~8,000 MT/yr.
- Projected glutamine demand was ~6,500-34,000 MT/yr, which could exceed current global production volumes.
- Eight interviewees flagged glutamine as high-risk due to limited supplier base, manufacturing complexity, and the current lower market demand.

☑ Difficult to replace with hydrolysates

- Glutamine degrades during typical hydrolysis processes, explaining why glutamic acid is high in many raw materials and hydrolysates (**Figure 10**).
- As a result, the direct supply of glutamine via hydrolysates is not considered tractable via current hydrolysis methods.



L-Asparagine

Uncertain supply of asparagine leads to a high risk profile

About

Asparagine is a non-essential amino acid often included in cell culture media because it can enhance growth and protein production. Many cell lines can synthesize asparagine endogenously, but providing it exogenously spares cellular resources and can improve viability and growth rates. Notably, when cells are under metabolic stress and/or if glutamine becomes limiting, extracellular asparagine can rescue cell survival and proliferation by serving as an alternative nitrogen source (Pavlova et al. 2018). Asparagine can become conditionally essential in certain rapidly proliferating or asparagine-synthetase-deficient cells.

Opportunities

Asparagine's production process involves a complex biochemical synthesis or specialized fermentation and purification steps, which drive up manufacturing costs. Additionally, a lack of competing suppliers due to historically limited demand keeps the price of asparagine elevated.

Scaling up asparagine production and investing in further innovation to drive down costs will be a priority opportunity area for amino acid suppliers to meet the needs of the cultivated meat sector. Additionally, more reliable data on production volumes of L-asparagine suitable for use in cultivated meat are needed to better understand its supply risk.

Cost driver

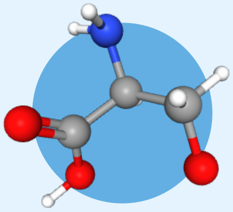
- Asparagine had estimated food-grade prices of $18-31/kg.
- Its cost contribution ranged from 5-22% of amino acid costs within media due to its relatively high cost and expected high usage rates in certain formulations.

Potential supply bottleneck

- Production volume data for asparagine could not be sourced, and it is currently believed to be a somewhat niche market with few suppliers.
- Projected asparagine demand was ~2,000-18,000 MT/yr.
- Coupled with uncertainty over current production volumes, two interviewees flagged asparagine as high-risk.

Difficult to replace with hydrolysates

- Asparagine typically degrades into aspartate during hydrolysis, reducing its potential to be directly supplied from hydrolysate sources.



L-Histidine

Histidine is the highest price amino acid

About

Histidine is an essential amino acid required for protein synthesis and has unique biochemical importance owing to its imidazole side chain. With a pKa around 6.0, histidine's side group can toggle between protonated and unprotonated states near physiological pH, making it a common ligand in metalloproteins and an important residue in many enzyme active sites (Schwentner et al. 2019). In cell culture, sufficient histidine is necessary for cells to grow and proliferate; without it, protein synthesis stalls.

Opportunities

Microbial fermentation of histidine involves a long, tightly regulated pathway with around ten enzymatic steps, making high-yield fermentation technically complex (Kulis-Horn et al. 2014). Additionally, purification costs—particularly for the hydrochloride salt form—further inflate its price.

Scaling up production and investing in cost-lowering innovations in histidine manufacturing is a key opportunity area for amino acid suppliers.

☑ Cost driver

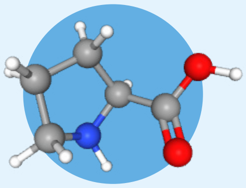
- Histidine had the highest food-grade price estimates of $26-75/kg.
- While it is used in media at lower amounts compared to other amino acids, its high unit cost results in histidine contributing to over 8% of amino acid costs in media.

☑ Potential supply bottleneck

- Histidine has limited production volume (~2,000 MT/yr).
- Projected histidine demand (~1,300-5,000 MT/yr) could exceed current production volumes.
- Four interviewees flagged histidine as high-risk.

☐ Difficult to replace with hydrolysates

- Hydrolysates were able to provide adequate amounts of histidine; however, it was commonly amongst the three limiting amino acids (**Figure 12**).



L-Proline

Proline is at high risk of a supply bottleneck

About

Proline is a non-essential amino acid with a unique cyclic structure that influences protein folding, osmoprotection, and stress mitigation. It is especially abundant in extracellular matrix proteins such as collagen. Muscle and fibroblast cells that produce these proteins can benefit from proline supplementation (Patriarca et al., 2021). Additionally, cells can catabolize proline, via proline dehydrogenase, back to glutamate, which links to the TCA cycle – meaning proline can serve as a reserve energy source during nutrient stress. Thus, while many cell lines can synthesize proline from glutamate, providing extra proline in the medium ensures optimal growth, especially for dense cell cultures or those requiring synthesis of matrix proteins.

Opportunities

Proline's risk profile is dependent on its inclusion rate in media, and further research is needed to understand the importance of proline for cultivating or differentiating cells, such as muscle and fibroblasts, which may benefit from added proline.

In general, suppliers can help prevent supply bottlenecks and sudden price increases by scaling up production and investing in cost-lowering innovations in proline manufacturing.

☑ Cost driver

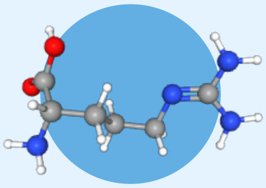
- Proline had estimated food-grade prices of $19-31/kg.
- Its inclusion rate in media may differ depending on the formulation. If used in high amounts, as in the modified CHO media, it could contribute over 16% of amino acid costs.

☑ Potential supply bottleneck

- Proline has limited production volume (~500 MT/yr).
- Projected proline demand (~200-13,300 MT/yr) could exceed current production volumes, although this is dependent on proline's inclusion in media.
- One interviewee flagged proline as high-risk.

☐ Difficult to replace with hydrolysates

- Our analysis suggests that hydrolysates could serve as an adequate proline source, even in proline-rich media.



L-Arginine

Arginine's high usage rate drives its cost

About

Arginine is considered essential in cell culture because cell types used in cultivated meat lack the organ systems that collaborate to produce arginine in the body. It is crucial for protein synthesis and serves as a metabolic precursor for several important biomolecules, such as polyamines, required for cell proliferation. Arginine is often one of the most rapidly depleted amino acids in culture due to its role in supporting energy production and growth.

Opportunities

Microbial production involves multiple biosynthetic steps, high oxygen requirements, and heavily mutated production strains to prevent strong feedback inhibition (Utagawa 2004). The added challenge of converting arginine into a usable salt form (like arginine HCl) also adds to purification costs, which presents an opportunity for suppliers to optimize downstream processing.

Arginine is currently available at relatively large scales and low costs; thus, the largest opportunity to mitigate arginine's cost burden is for researchers to improve feed conversion ratios, reducing overall arginine usage in media.

☑ Cost driver

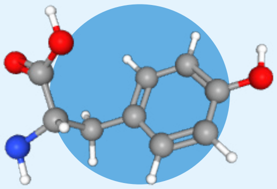
- Arginine had lower estimated food-grade prices of $5-18/kg.
- The high usage rate of arginine in media influences its high cost contribution in media (4-10% of total amino acid costs).

☐ Potential supply bottleneck

- Projected arginine demand (~6,250-20,244 MT/yr) is high, but was not deemed at risk due to relatively high current production volumes (~60,000 MT/yr).

☑ Difficult to replace with hydrolysates

- Hydrolysates can partially supply arginine; however, achieving sufficient levels to meet demand will be difficult.
- Arginine is likely to remain predominantly supplied by fermentation.



L-Tyrosine

Tyrosine is at high risk of a supply bottleneck

About

Tyrosine is a non-essential amino acid that plays a crucial role in the synthesis of proteins such as coenzyme Q10 and is often enriched on protein surfaces where it binds small molecules, nucleic acids, or other proteins, facilitating their interactions. While cells can produce it, adding tyrosine to cell culture media improves growth, viability, energy preservation, nutrient uptake, and reduces toxic by-products.

Opportunities

Tyrosine was originally produced via extraction and enzymatic methods, but industrial production is shifting to fermentation-based processes. Still, there are many challenges around feedback inhibition, high production costs, and low production efficiency (Li et al. 2021). Interviewees cited manufacturing complexity and limited suppliers as key reasons for concern. Additionally, its low solubility at neutral pH poses well-described issues for use in cell culture.

Suppliers can continue to optimize fermentation strains, yields, and scale up of tyrosine production. Similar to glutamine, research into stabilized dipeptide forms and controlled feeding of tyrosine will be important for cultivated meat applications.

☐ Cost driver

- Tyrosine had estimated food-grade prices of $14-31/kg; however, its inclusion rate in media is low, and it was not identified as a major cost driver.

☑ Potential supply bottleneck

- Tyrosine has the lowest current production volume (~200 MT/yr) with few global suppliers.
- Projected tyrosine demand (~2,300-7,700 MT/yr) could quickly exceed current production volumes.
- Three interviewees flagged tyrosine as high-risk.

☐ Difficult to replace with hydrolysates

- Our analysis suggests that hydrolysates could serve as an adequate tyrosine source.

Extended methods

Structured interviews

To gather information on the amino acid supply chain, a detailed questionnaire was assembled for different stakeholders along the value chain, including amino acid and hydrolysate suppliers, cell culture media companies, cultivated meat manufacturers, and other experts in GFI's network. A total of 25 stakeholders (eight CM companies, three hydrolysate suppliers or experts, 10 cell culture media companies or experts, four amino acid suppliers or experts) were interviewed and/or provided written answers to the questionnaire. Notes and interview transcripts were summarized using ChatGPT (Enterprise account, Model 4).

Information acquired from interviews is integrated throughout this report. All information is based on aggregated responses, and any identifying information was excluded to ensure the confidentiality of participants.

Scenarios for total amino acid requirements based on bioconversion efficiencies

Multiple data points were aggregated to derive estimates for the total quantity of amino acids needed to produce 1 kilogram of cultivated meat (**g AA/kg CM; Table A1, Figure A1**).[10] This range was further validated based on qualitative responses received during the interview phase. Limitations related to these scenarios are described in **Table A5**.

Table A1. Bioconversion efficiency scenarios used in the study.

Bioconversion efficiency scenario	Source	Notes
200 g AA/kg CM	(Sinke et al. 2023)	Lower estimate from the study.
232 g AA/kg CM	(Pasitka et al. 2024)	In this study by Believer Meats, 1.7kg of wet cell biomass was produced using 110 L of media. Using the media formulation provided in the study, it was estimated that 232 g AA/kg CM was required.
268 g AA/kg CM	(Humbird 2021; Kossmann, Moess, and Breunig 2025)	Humbird's analysis estimated the molar ratio of amino acids needed to meet the stoichiometric requirements of a cell. Molar ratios were translated to a mass basis to derive an estimate of 268 g AA/kg CM.
283 g AA/kg CM	(Sinke et al. 2023)	Mid estimate from the study.
350 g AA/kg CM	Interview estimate 1	Estimated from interviews.
400 g AA/kg CM	(Sinke et al. 2023)	Higher estimate from the study.
500 g AA/kg CM	Interview estimate 2	Estimated from interviews.
650 g AA/kg CM	N/A	An additional estimate of 650 g AA/kg CM was included to represent the least efficient scenario, with lower efficiencies deemed unlikely to result in cost-competitive CM production.

---

[10] 1 kg of cultivated meat refers to 1 kg of wet cell mass. Cellular water content and biomass composition (which influence bioconversion efficiency estimates) are not specified, as the scenarios for bioconversion efficiency were derived from different studies with different water content assumptions. This analysis did not investigate hybrid cultivated meat products.

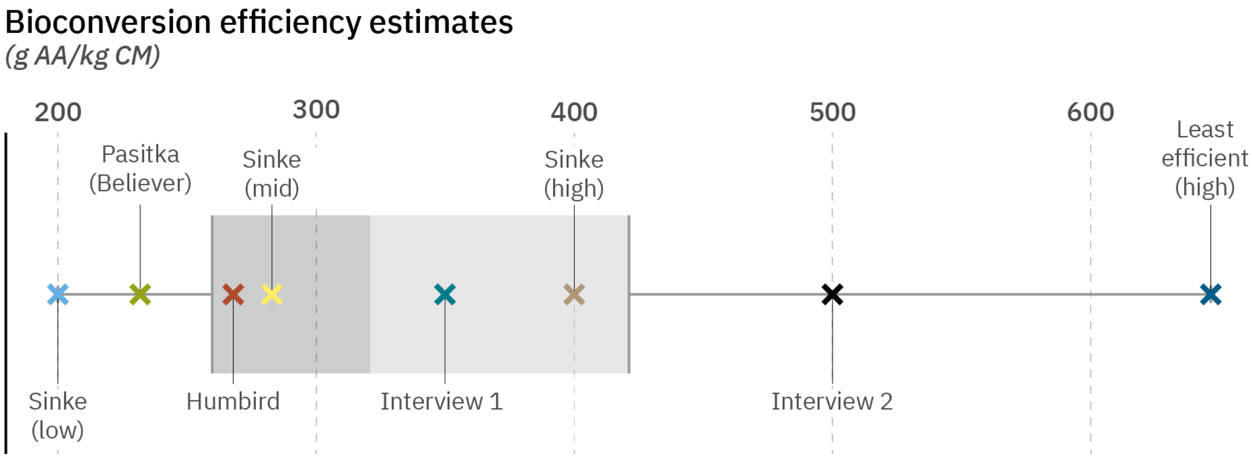


Figure A1. Range of estimates reported for bioconversion efficiency corresponding to grams of amino acids required for one kilogram of cultivated meat (wet cell mass) production. These estimates were compiled from both published literature and expert interviews, providing a broad view of the expected amino acid requirements across the industry. The variation across sources reflects differences in cell type, growth efficiency assumptions, media composition, and production methodologies.

Estimation of individual amino acid requirements using commercially-relevant cell culture media formulations

To estimate the amounts of individual amino acids required for one kg of cultivated meat, we combined the bioconversion efficiency scenarios with the amino acid concentrations used in various cell culture media. The basal medium formulation DMEM/F12 is publicly available and can be used as a starting point for culturing various animal cells (Stout et al. 2022), which was further validated during the interview phase. However, when cells are grown in dense cultures, as is anticipated for cultivated meat, they require higher quantities of amino acids and other nutrients compared to off-the-shelf basal media designed for adherent culture. To represent this, we used the media formulation FSF4, which was previously developed by the cultivated meat startup SciFi Foods (see below for the complete formulation). The FSF4 media is a serum-free, chemically-defined formulation developed for the growth of bovine fibroblast cells in single-cell suspension culture. The formulation has been validated at a 500L scale and was previously submitted to the US FDA for safety evaluation. In 2024, SciFi Foods ceased operations, and GFI acquired SciFi's media formulations and cell lines in an auction, making these assets publicly available to the broader community as of October 2025.

The quantity of amino acids in DMEM/F12 is 1.11 g/L compared to the FSF4 media at 3.55 g/L, which was similar to 3.57 g/L listed in the animal component free media formulation from a study by Believer Meats (Pasitka et al. 2024). Based on confidential expert feedback, we concluded that these concentrations of amino acids may not be sufficient for future cultivated meat production. Accordingly, we modified a media formulation developed for Chinese Hamster Ovary (CHO) cell culture (胡辉, 李军, and 翁志兵 2014, translated from page 7), with increased amounts of alanine, asparagine, and glutamic acid based on previous experience in the cultivated meat industry from the authors. This modified media contains a total amino acid concentration of 7.23 g/L, and represents a nutrient-dense formulation designed to support extremely high cell densities and substantial recombinant protein production. This results in elevated concentrations of total amino acids, serving as a high upper bound for what may be expected in cultivated meat manufacturing. Total amino acid concentration estimates in media are compared in **Figure A2**.

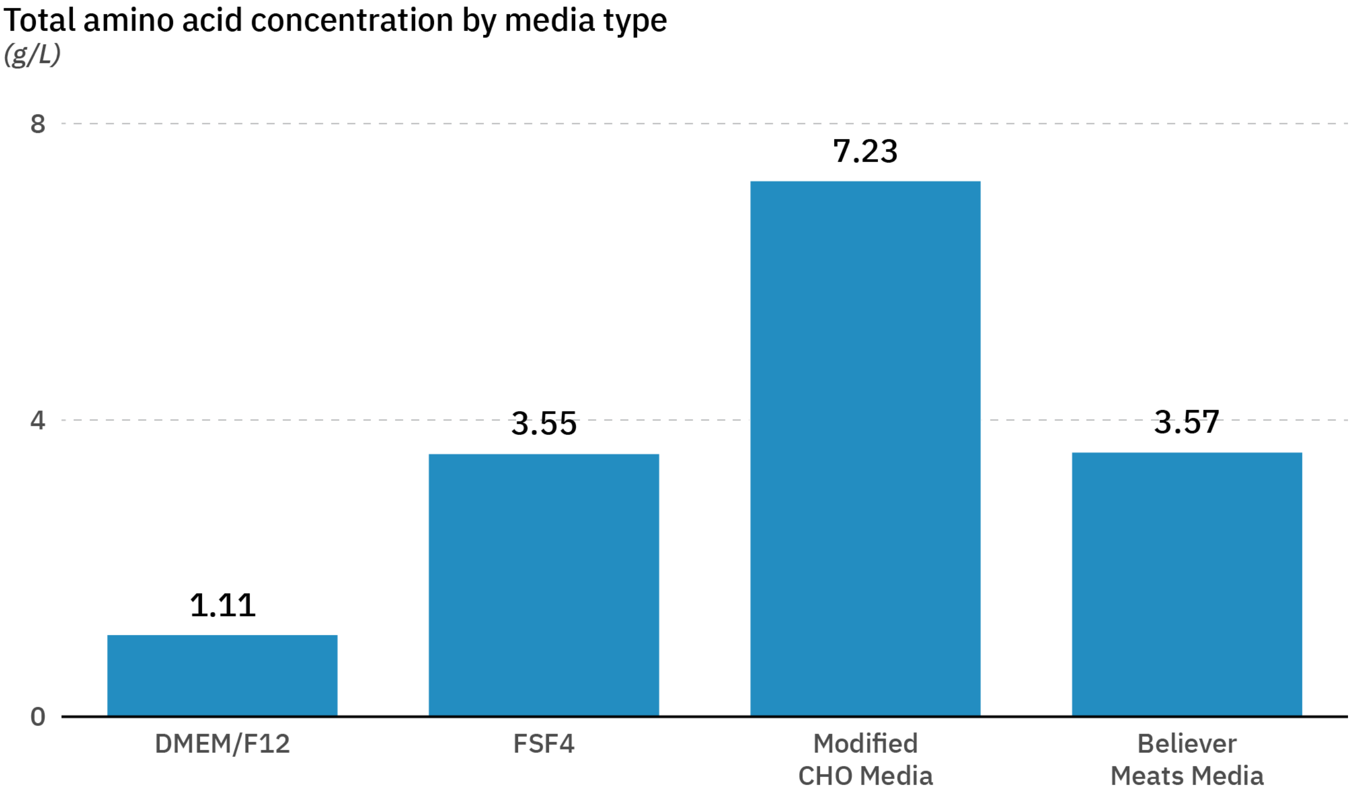


Figure A2: Comparison of the total concentration of amino acids across media formulations examined. The total amount of amino acids (g/L) was calculated for each of the four distinct media formulations by summing the concentrations of all amino acids present. This figure highlights the overall amino acid load in each media type, providing a comparative view of nutrient density across formulations. Differences in total amino acid concentrations may reflect variations in process design, cost optimization, cell type, species metabolism, and/or product type. The FSF4 and modified CHO media were used for this analysis.

Although the quantity of amino acids is higher in the FSF4 and CHO formulations, the ratiometric makeup of amino acids remains relatively similar to the standard DMEM/F12 formulation (**Figure A3**). For example, the FSF4 formulation contains only two amino acids with a >5% difference in mass percentage compared to DMEM/F12 (serine, +12% and glutamine, -12%). The CHO formulation had four amino acids with a >5% difference (glutamine, -29%; asparagine, +10%; serine, +7.8%, and proline, +6.6%). These data support the notion that while DMEM/F12 is a good starting point, commercially-relevant media will contain higher quantities of total amino acids, with variance in specific amino acid ratios depending on the metabolic needs of the cells.

Comparisons to Humbird’s cellular stoichiometry

We compared the total amounts of individual amino acids needed to produce 1 kg CM with the amino acid requirements implied by Humbird’s cellular stoichiometry model (**Figure A4**). Although the bioconversion efficiency implied by the stoichiometry model (268 g AA/kg CM, **Table A1**) falls within the range used in this report, individual amino acid requirements show higher variance.

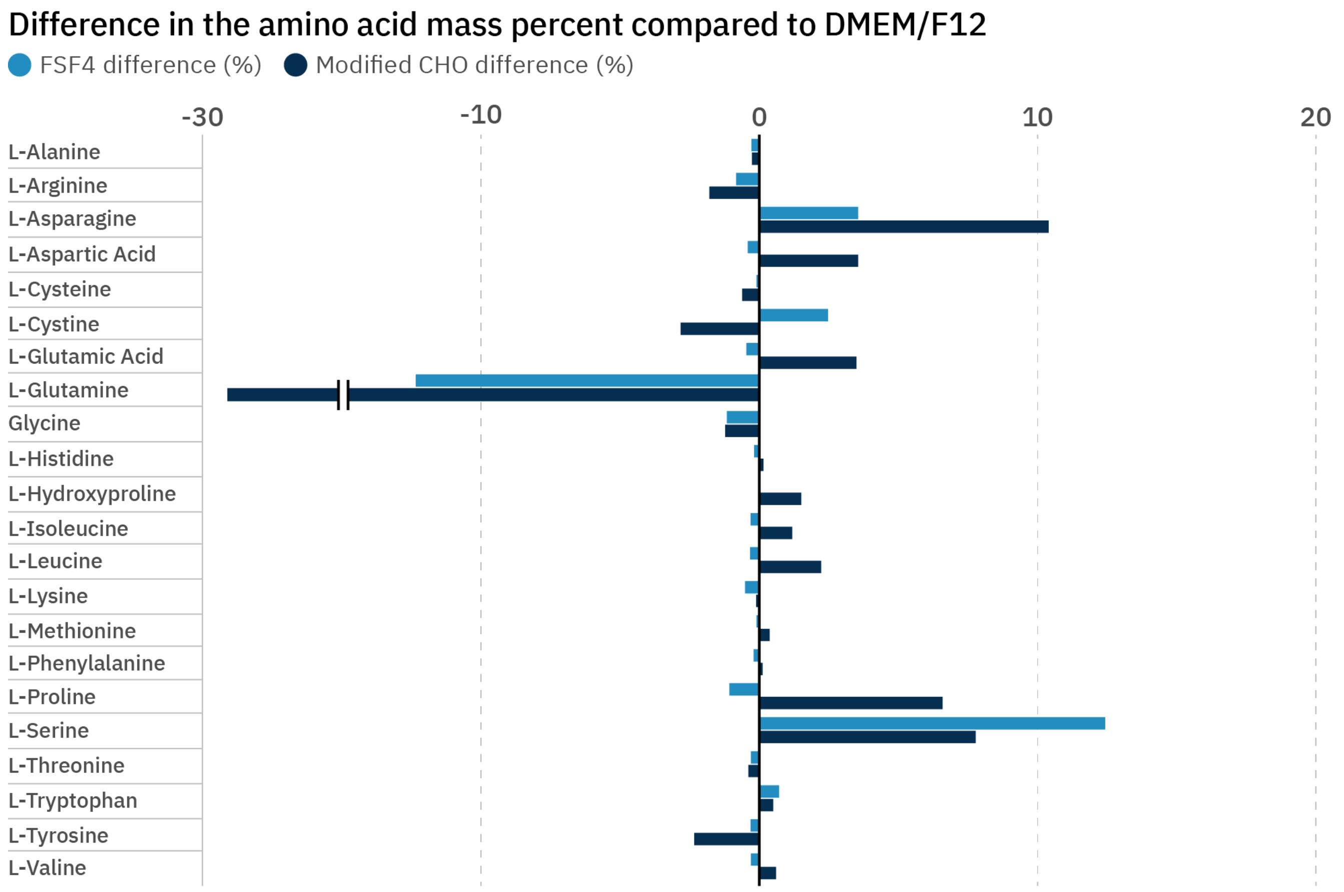


Figure A3: Difference in percent mass of individual amino acids (normalized to total amino acid mass) between DMEM/F12 and the FSF4 and CHO formulations. This figure shows which amino acids are overrepresented or underrepresented in alternative formulations, providing insight into how newer or modified media diverge from conventional basal media largely designed for less dense adherent cell cultures.

The stoichiometry model reflects the final composition of cellular protein but does not account for the full range of metabolic activity during growth. In practice, amino acids provided by the culture media are subject to significant metabolic flux. Some are transformed into other molecules, used as energy sources, or lost through secretion or degradation. As shown in **Figure A4**, some amino acids (e.g., arginine, serine) are overfed in media to compensate for these factors and prevent nutrient starvation. Other amino acids (e.g., alanine, aspartic acid, glycine, proline) are underfed and appear in the final biomass as a result of the metabolism of other amino acids and nutrients. As shown in the Results, this means that real-world expectations for amino acid production volumes are best satisfied on the basis of typical media formulations rather than the expected amino acid makeup of protein in the cell, which represents a more idealistic case.

Comparison of amino acid requirements for cultivated meat production vs. cellular stoichiometry
(g AA/kg CM)

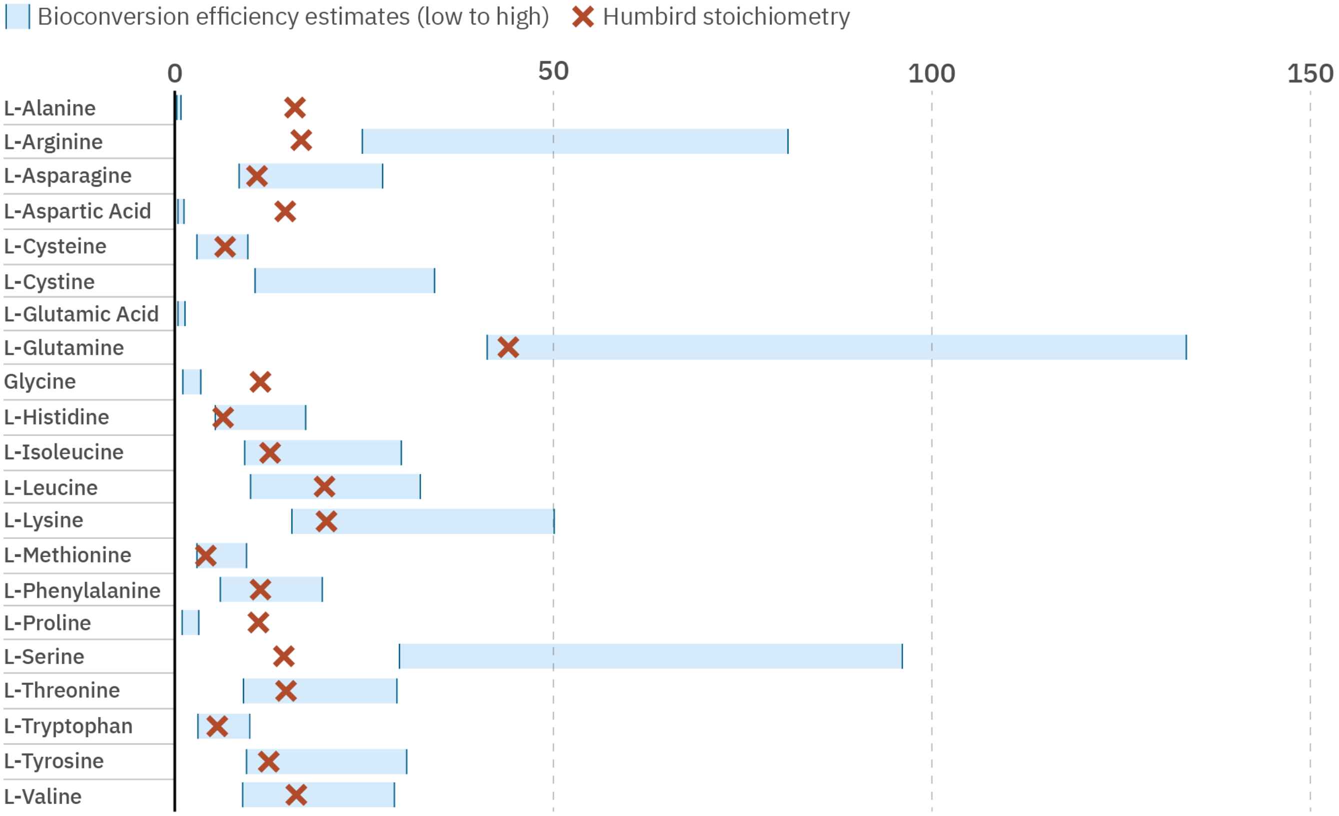


Figure A4. Comparison of amino acid requirements for cultivated meat production based on media formulations vs. cellular stoichiometry. This figure compares estimated amino acid requirements for cultivated meat production between the FSF4 media formulation and the amino acid stoichiometry assumed by Humbird. The estimates represent grams of each amino acid required per kilogram of cultivated meat, spanning the lowest and highest bioconversion efficiency scenarios.

Ultimately, each media formulation used in cultivated meat manufacturing is likely to be customized based on the cell type, species, metabolic requirements for growth and differentiation, and desired nutritional attributes of the final product. To simplify the analysis, we used the FSF4 formulation as the baseline media formulation, with some scenarios incorporating the modified CHO media to represent a higher upper bound for cellular nutrition requirements. The range of estimates for bioconversion efficiency (g AA/kg CM) was assumed to capture variance in amino acid concentrations within other formulations that may be used throughout the industry. Limitations related to this approach are described in **Table A5**.

Amino acid price estimates

Understanding the price of amino acids is essential to gauging how much they will contribute to the cost of cultivated meat production. Numerous interview questions were asked to obtain better estimates for the current and future prices of food-grade amino acids, which were confirmed to be in use throughout the industry. Prices for food-grade essential amino acids were obtained from aggregate suppliers such as Alibaba, Made-in-China, and Bulksupplements, and presented alongside prices previously estimated (Humbird 2021) (**Table A2**).

Interviewees were blinded to the source and asked to identify the prices that most accurately reflect current market prices for food-grade amino acids.

Source 2 (Alibaba) was identified by six participants as the most representative, while one participant cited Source 4 (Bulksupplements). One participant said Source 1 (Humbird) reflected low-volume pricing, while another reported sourcing at prices lower than any listed.

Numerous participants mentioned that Source 1 (Humbird) was most aligned with pharma-grade pricing. Consideration for different material grades are discussed further throughout the main sections of the report.

Table A2. Essential amino acid prices by source presented during interviews. Interview participants were blinded to the identity of the source and asked to identify the source that most accurately reflects market prices for food-grade amino acids (bottom row). For aggregate suppliers, the prices were sourced at different scales, but values have been normalized per kg for comparability. Prices excluded shipping, taxes, and other fees. See below for the full framing of interview questions related to amino acid prices.

Amino acid	Price ($/kg)			
	Humbird (Source 1)	Alibaba (Source 2)	Made-in-China (Source 3)	Bulksupplements (Source 4)
L-arginine	70	7	15	14
L-cysteine	137	15	16	27
L-glutamine	40	9	9	19
L-histidine	118	47	35	46
L-isoleucine	83	25	15	18
L-lysine	62	5	-	10
L-methionine	156	-	-	16
L-phenylalanine	85	10	60	17
L-threonine	76	-	-	10
L-tryptophan	146	13	8	26
L-tyrosine	81	15	10	24
L-valine	71	10	10	14
Number of votes tallied	1	6	0	1

In addition to answers to blinded prices, we received representative quotes for food-grade amino acid purchase orders and found them to be generally aligned with prices from Source 2 (Alibaba). Importantly, the quotes obtained were typically for volumes in the tens of kilograms, which represent current purchasing volumes for cultivated meat or cell culture media companies, rather than future bulk purchases at the tonne scale that may have lower prices. Using the collected information, we defined three pricing scenarios representing current prices of food- and feed-grade amino acids (**Table A3**).

The low food-grade estimate represents a -25% differential from lowest value listed for each amino acid in the quotes obtained during interviews, while the high food-grade estimate represents a +25% differential from the highest price for each amino acid listed in quotes. Finally, a hypothetical low price based on feed-grade amino acids listed on aggregate supplier sites was included. As discussed previously, many companies have had success when testing feed-grade nutrients in their R&D, although regulatory considerations may impact their commercial use. All values were rounded to the nearest whole number and these three pricing scenarios were used in the downstream analyses.

Table A3. Scenarios for food- and feed-grade amino acid prices used in this study. The low food-grade scenario represents a -25% differential from lowest value listed for each amino acid in the quotes obtained during interviews, while the high food-grade scenario represents a +25% differential from the highest price for each amino acid listed in quotes. A hypothetical low price was obtained for feed-grade amino acids listed on aggregate supplier sites. All values were rounded to the nearest whole number.

Amino acid	Price ($/kg AA)		
	Feed-grade price scenario	Low food-grade price scenario	High food-grade price scenario
L-Alanine	5	13	21
L-Arginine	3	5	18
L-Asparagine	13*	18	31
L-Aspartic Acid	3	10	16
L-Cysteine	10	11	29
L-Cystine	10	13	13θ
L-Glutamic Acid	4	12	20
L-Glutamine	5	7	16
Glycine	2	4	7
L-Histidine	10	26	75
L-Hydroxyproline	15*	15	25θ
L-Isoleucine	4	11	19
L-Leucine	4	4	6
L-Lysine	1	4	11
L-Methionine	3△	8	20
L-Phenylalanine	8	8	13
L-Proline	13	19	31
L-Serine	10	30	50
L-Threonine	1	3	13
L-Tryptophan	3	16	33
L-Tyrosine	10	14	30
L-Valine	3	4	13

* No feed-grade prices were obtained for these amino acids, so the lowest food-grade value was used.

△ Feed-grade methionine is produced as D,L-Methionine, which may not be suitable for animal cell culture due to a lack of the liver and kidney enzyme D-amino acid oxidase used to convert D-amino acids *in vivo*. Prices for pure L-methionine are uncertain.

θ No real-world quotes were obtained for these amino acids, so the highest food-grade value from aggregate suppliers was used.

Candidate hydrolysate blends and cost calculations

Protein hydrolysates have been proposed as a way to supply cellular nutrition at lower cost and environmental impact (Sinke et al. 2023; Humbird 2021). To evaluate the feasibility of using hydrolysates as an amino acid supply in cultivated meat media formulations, we assembled a list of 50 candidate raw materials and protein hydrolysates from three primary sources: 1) previously published research identifying promising agricultural and food-processing sidestreams (Eastham et al. 2023), 2) promising raw materials or hydrolysates mentioned during stakeholder interviews, and 3) publicly available commercial data from suppliers marketing hydrolysates and peptones for cell culture applications.

For each raw material or hydrolysate, we compiled available amino acid composition data (g AA per 100 g dry matter) from technical datasheets, nutritional databases, and scientific literature. For hydrolysates derived from algae, cattle feed pellets, grasses, and alfalfa, we assumed full recovery of amino acids from a 20 mL extraction volume to standardize comparisons across sources.

The amino acid profiles were first compared to the amino acids needed to create 1 kg of CM based on the FSF4 media formulation and 350 g AA/kg CM bioconversion efficiency scenario previously described (**Figure A5**).[11] As shown in the Results, raw materials and hydrolysates are typically low in glutamine, arginine, asparagine, cystine, and serine compared to the anticipated requirements of cell culture media (**Figure 10**). Supplying these amino acids via hydrolysates

---

[11] Free glutamine and asparagine are unstable and are often converted to glutamic and aspartic acid during the hydrolysis process, hence their elevated levels in the dataset.

would require significant quantities of raw material to be used, excluding this possibility based on cost alone (data not shown). Accordingly, downstream analysis assumed that glutamine, arginine, asparagine, cystine, and serine would be supplied individually via fermentation processes (referred to as "Spiked AAs"). Limitations related to this approach are described in **Table A5**.

ChatGPT (GPT-5) was used to identify candidate blends for several scenarios (**Table A4**). ChatGPT was instructed to identify blends that satisfy the amino acid requirements corresponding to each scenario, excluding the five Spiked AAs. ChatGPT was further instructed to minimize the total mass of materials used, and constrained to use no more than three materials while ensuring that no amino acid exists in undersupply (without penalizing oversupply). Analysis was replicated in Excel using the Solver add-in as well as manually verified to ensure the recommended blends met the optimization criteria.

The top three results from each scenario are shown in the Results (**Figure 11**). Raw material data, scenarios, and spreadsheets can be modified by practitioners to explore different cases based on their own needs

Maximum viable hydrolysate costs per kg of CM were derived using the three different price estimate scenarios outlined in **Table A3**. The price allowance for hydrolysates was taken as the difference between total amino acid costs per kg of CM minus the cost of the five Spiked AAs sourced via fermentation. Offsets from hydrolysate blends that contributed a portion of the spiked AAs (i.e., serine and arginine) were accounted for. Allowable hydrolysate price ranges per kg of material were then calculated based on the amount of raw material needed to satisfy the remaining amino acid composition. This resulted in a maximum viable price of the hydrolysate component that would permit the final formulation to achieve parity with a fully fermentation-derived amino acid media composition.

Scenario	Purpose
Scenario A: FSF4 media at 350 g AA/kg CM	A single scenario for bioconversion efficiency was selected. Because the amino acid ratios in media and raw materials are fixed, other scenarios for bioconversion efficiency will result in the same output, just more or less raw material used.
Scenario B: Modified CHO media at 350 g AA/kg CM[12]	To see how candidate blends change based on media formulation differences.
Scenario C: only commercial hydrolysates for FSF4 media at 350 g AA/kg CM	To see how candidate selection differs when commercially available hydrolysates are separated from other unprocessed raw materials, which tend to have lower amino acid concentrations per gram of dry mass (see **Figure 10**).
Scenario D: only raw materials for FSF4 media at 350 g AA/kg CM	

Table A4. Scenarios for candidate hydrolysate blend identification using ChatGPT.

---

[12] Hydroxyproline is present in the modified CHO media but was excluded from Scenario B and assumed to be spiked in. While three hydrolysates in the dataset had hydroxyproline present, this was deemed a likely artefact from the study cited (Amirvaresi & Ovissipour 2024), as this amino acid form is typically not present in non-animal materials.

Hydrolysate and raw material amino acid content vs. amino acids needed for 1 kg of CM using FSF4 media

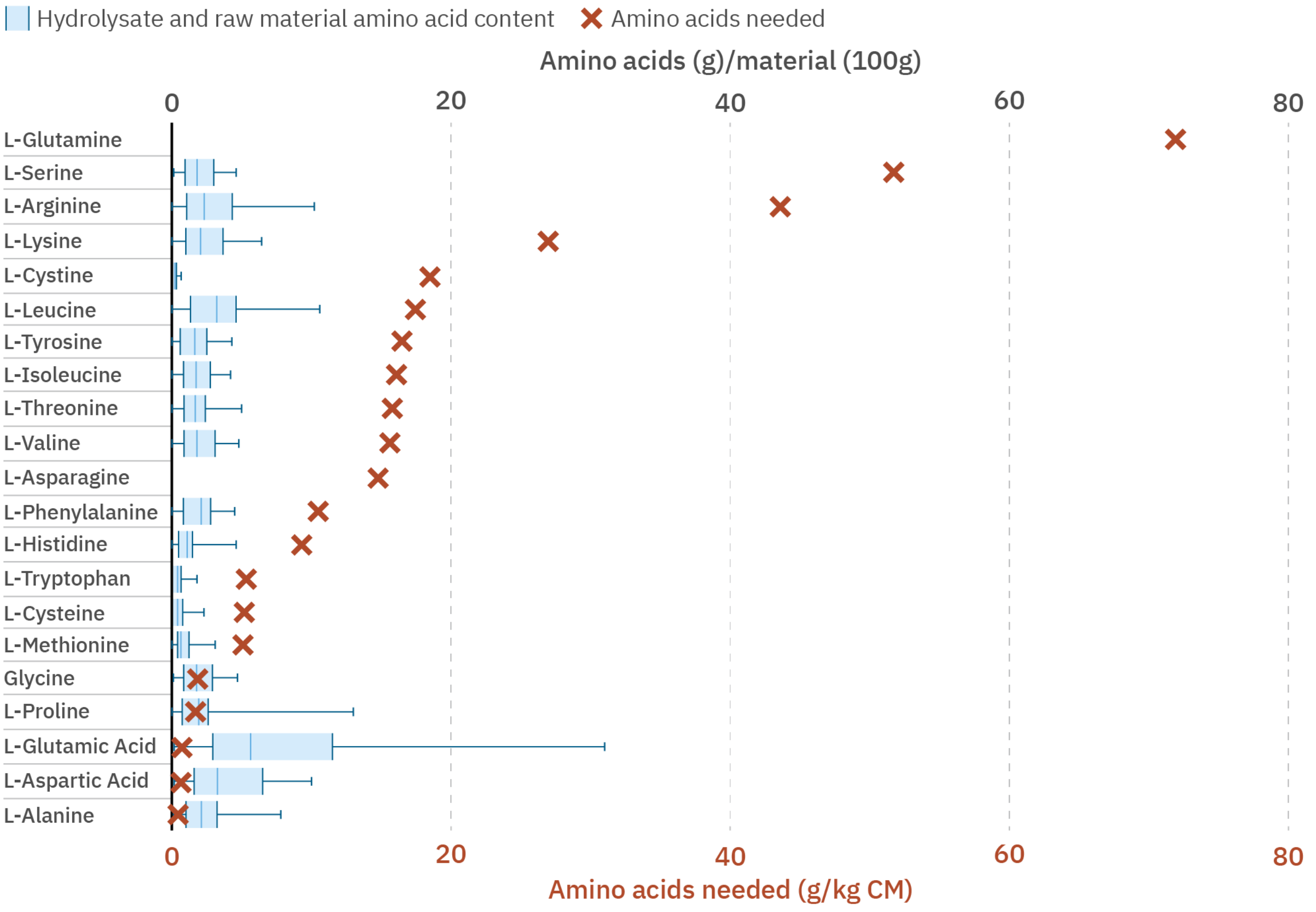


Figure A5. Amino acid profiles of 50 raw materials or hydrolysates examined in the study (blue) compared to the estimated amino acids needed to create 1 kg of CM (red Xs), assuming the FSF4 media formulation is used and 350 g AA/kg CM is required. This figure indicates which amino acids are deficient in raw materials and hydrolysates and would need to be independently supplied.

Assumptions and limitations

Table A5 outlines the key assumptions and limitations that may influence the results and their interpretation. Given the nascent and rapidly evolving nature of the cultivated meat industry, many inputs, such as media formulations, amino acid sourcing strategies, and pricing dynamics, are subject to variability and uncertainty. Assumptions were made to standardize modeling across diverse sources and to enable comparative scenario analysis, while known limitations were documented to promote transparency. These include constraints around data availability, supply chain forecasting, and real-world performance of hydrolysates. Understanding these assumptions is critical for evaluating the robustness of the estimates presented, identifying areas requiring further research, and guiding the design of future techno-economic and life cycle assessments.

Table A5. Key assumptions and limitations that may affect the results and interpretation of this analysis.

Category	Description	Assumption	Limitation or implication
Bioconversion efficiency	Estimates for bioconversion efficiency ranging from 200–650 g AA/kg CM	We assumed that the total quantity of amino acids was delivered by feeding the cells with the amino acid makeup of the media formulation as-is.	In practice, concentrated feeds of specific amino acids (e.g., glutamine) may be used such that the ratio of amino acids that make up the total quantity diverges from that of the starting media. This was not accounted for in this analysis, and results should be interpreted with this in mind.
		We assumed that this range captured the variance in amino acid concentrations within other formulations that may be used throughout the industry.	To validate if this assumption holds, more commercially-relevant media formulations would need to be made publicly available.
		We assumed this range accurately represents bioconversion of amino acids in cultivated meat manufacturing.	Empirical data on bioconversion efficiency or feed conversion ratio of amino acids is lacking. To narrow this range further, more experimental data from CM-relevant cell lines in commercially-relevant bioprocesses are needed, such as Pasitka et al. 2024.
	Media formulation vs. stoichiometry	We assumed that amino acid concentrations in media rather than protein stoichiometry (Humbird 2021) were more appropriate in predicting amino acid demand in cultivated meat manufacturing.	Estimates for production volumes of individual amino acids are dependent on this assumption (see **Figure A4**). However, it's worth noting that the total amino acid demand from Humbird's stoichiometry estimates corresponded to 268 g AA/kg CM, which still fell within the range of bioconversion efficiency scenarios used.

Category	Description	Assumption	Limitation or implication
Media formulations	FSF4 media formulation	We assumed that the total amount and concentration of individual amino acids in the FSF4 media formulation is representative of commercial cultivated meat production.	In practice, the media formulations for different cell types, species, processes, and products may vary. To validate if this assumption holds, more commercially-relevant media formulations would need to be made publicly available.
	Modified CHO formulation	We assumed that the total amount and concentration of individual amino acids in the modified CHO media formulation represents a conservative, high upper bound for commercial cultivated meat production.	This assumption needs additional validation from CM-relevant cell lines in commercially-relevant bioprocesses.
Hydrolysates	Requirement for five spiked AAs	We assumed that glutamine, serine, cystine, arginine, and asparagine would need to be spiked in due to consistent underrepresentation or instability in raw materials and hydrolysates.	Other raw materials not included in our dataset and/or optimization of hydrolysis protocols may satisfy certain AA requirements and alter the results (see *Eugelena* case study where asparagine can be fully supplied, negating the need to spike it in). Identification of candidate raw material and hydrolysate blends should be interpreted as guiding examples rather than conclusive findings.
	Differences in amino acid composition in raw materials vs. hydrolysates in the dataset	We assumed that the amino acid composition in raw materials (g AA/100 g DM) is unchanged post-hydrolysis or post-processing.	The free or bioavailable amino acid makeup is likely to change from the unprocessed raw material composition following hydrolysis or other processing steps required to break down the material. One example in the dataset is provided by compositional differences between wheat gluten hydrolysate and wheat peptone despite coming from the same source material.

Category	Description	Assumption	Limitation or implication
Hydrolysates continued	Continued	Continued	Less processed raw materials tend to have lower amino acid concentrations per g of DM compared to commercially-available hydrolysates. Scenarios C and D in **Table A4** that separately analyze commercial hydrolysates and raw materials are intended to account for this; however, the overall evaluation of candidate raw materials should be considered rudimentary until more post-processing composition data are available. Process optimization and standardization will be important factors to consider when generating future results.
	Price range for hydrolysates to be cost-competitive with fermentation-derived amino acids	We assumed that the value of the hydrolysate is solely based on its capacity to replace amino acids.	In reality, hydrolysates may provide other functions such as antioxidant capacity, serum and/or growth-factor replacement, and substitution of other basal media components (e.g., vitamins, lipids), increasing their relative value in the media. These considerations were outside the scope of this analysis. Future studies should aim to examine the full spectrum of hydrolysate functionality to determine alternative cost-competitive ranges.
	Use of ChatGPT for candidate blends identification	We assume that ChatGPT is suitable for the identification of candidate blends.	ChatGPT may produce errors or hallucinations. To ensure this did not occur, all solutions were replicated using Excel’s Solver add-in and confirmed via manual calculation.
Amino acid pricing	Non-industrial scale volumes	-	Interview-based amino acid prices reflect volumes in the tens of kilograms, not thousands of tonnes. Extrapolation to future bulk pricing may differ. Fluctuation in prices, which can be expected in real-world supply chains, were only accounted for by expanding the range by ±25%.
Proliferation vs. differentiation media composition	Proliferation media-only analysis	-	Amino acid requirements may differ between differentiation and proliferation phases. However, limited data for differentiation media exist, and we did not collect additional information on differentiation during the study. These potential differences could affect the results, depending on the extent to which differentiation is pursued for cultivated meat production.

FSF4 full media formulation

The full FSF4 media formulation is copied below, and can also be found here alongside other variants of this formulation acquired by GFI.

FSF4 media components	Final concentration (mg/L)
Salts	
Calcium chloride dihydrate	154.4
Copper(II) sulfate pentahydrate	0.013
Iron(III) nitrate nonahydrate	0.05
Iron(II) sulphate heptahydrate	0.417
Magnesium chloride hexahydrate	61.29
Magnesium sulphate heptahydrate	100.3
Potassium chloride	311.8
Sodium phosphate dibasic heptahydrate	134.1
Sodium phosphate monobasic dihydrate	141.3
Sodium selenite	0.02
Zinc(II) sulphate heptahydrate	0.86
Sodium bicarbonate	3360
Sodium chloride	3000
Amino acids	
L-Alanine	4.45
L-Arginine monohydrochloride	442.5
L-Asparagine monohydrate	150
L-Aspartic acid	6.65
L-Cysteine monohydrochloride monohydrate	52.68
L-Cystine dihydrochloride	187.74
L-Glutamic Acid	7.35
L-Glutamine	730
Glycine	18.75
L-Histidine monohydrochloride monohydrate	94.44
L-Isoleucine	163.41
L-Leucine	177.15
L-Lysine monohydrochloride	273.75
L-Methionine	51.72
L-Phenylalanine	106.44
L-Proline	17.25
L-Serine	525
L-Threonine	160.35
L-Tryptophan	54.12
L-Tyrosine disodium salt monohydrate	167.37
L-Valine	158.55
Carbon/energy	
D-Glucose (Dextrose)	5000
Sodium pyruvate	110
Vitamins	
Biotin (B7)	0.007
Calcium D-pantothenate (B5)	35.9
Choline chloride (B4)	2.24
Cyanocobalamin (B12)	2.65
Folic acid (B9)	2.02
Inositol (B8)	6.04

Nicotinamide (B3)	0.22
Pyridoxine hydrochloride (B6)	2.17
Riboflavin (B2)	0.68
Thiamine hydrochloride (B1)	12.6
2-Phospho-L-ascorbic acid trisodium salt (C)	200
Lipid mixture	
Tocopherol acetate	0.7
Arachidonic	0.02
Linoleic	0.6
Alpha-linolenic	0.6
Oleic	0.1
Myristic	0.1
Palmitic	0.1
Stearic	0.1
Growth factors	
Bovine FGF-2 (FGF-basic)	0.04
Bovine PDGF-BetaBeta	0.02
Bovine IGF-1	0.04
Bovine TGF-b1	0.004
Others	
Hypoxanthine	2.39
Lipoic acid (Thioctic Acid or ALA)	0.10
Putrescine dihydrochloride	0.08
Thymidine	0.37
Phenol Red	8.1
Ethanolamine	2
Glutathione	1
Fe citrate	10
HEPES	2.383
Pluronic F-68	1000
1M HCl to adjust to pH 7.7	-

Interview questionnaire

To inform this analysis, a structured interview questionnaire was developed to gather detailed insights from stakeholders across the cultivated meat value chain. The goal was to collect grounded data on amino acid pricing, sourcing practices, hydrolysate use, and media formulation strategies to support more accurate cost modeling and supply chain assessment.

A total of 25 stakeholders participated, including cultivated meat producers, media formulators, amino acid suppliers, and hydrolysate providers. Responses were provided via written submissions and live interviews, and were anonymized and aggregated to preserve confidentiality. This approach enabled the inclusion of industry-grounded insights throughout the report, with interview data playing a central role in cost estimates, risk analysis, and future scenario planning. Questions were tailored to specific stakeholder groups during the interview sessions. The full question set is copied below for transparency.

Cost questions

We have gathered amino acid price data (below) from multiple sources. Assuming these prices are for food-grade amino acids, which source do you believe most accurately reflects current market prices? Which source is the furthest away?

Amino acid	**Price ($/kg)**			
	1	**2**	**3**	**4**
L-arginine	70	7	15	14
L-cysteine	137	15	16	27
L-glutamine	40	9	9	19
L-histidine	118	47	35	46
L-isoleucine	83	25	15	18
L-lysine	62	5	-	10
L-methionine	156	-	-	16
L-phenylalanine	85	10	60	17
L-threonine	76	-	-	10
L-tryptophan	146	13	8	26
L-tyrosine	81	15	10	24
L-valine	71	10	10	14

Are you able to share any real price quotes (food- or feed-grade) for bulk purchases of amino acids in the range of 10 to 1000 kg or 1 to 10 tonnes? At what scale of purchasing do you believe would be necessary to reach the lowest prices from Source 2 (e.g., < $10/kg)?

What inputs are the major cost drivers of amino acid production? Have input prices (e.g., sugar feedstock and natural gas prices) impacted your cost of production and profit margins?

Which amino acids currently contribute the most to the cost of cell culture media? What do you believe are the reasons for this?

We've found that the cost differential between food- and feed-grade amino acids is between 50-80%. What is the primary driver(s) of the cost difference?

Which amino acids are the hardest or most expensive to produce at scale? Are there specific amino acids that you believe would be particularly difficult to bring costs down to that of lysine?

Amino acids produced in *E. coli* may have endotoxin. How is endotoxin currently controlled or removed from amino acids produced in *E. coli* and destined for use in cell culture? How much does endotoxin removal influence costs for amino acids produced in gram-negative bacteria such as *E. coli* vs. gram-positive bacteria such as *C. glutamicum*?

Production volume questions

What is the total annual volume of amino acids that you purchase for cell culture media? What is the distribution of your purchasing volume between pharma-grade, food-grade, and feed-grade amino acids? To what degree do you anticipate this volume increasing in 2025? By the year 2030?

If you currently sell amino acids directly to cultivated meat manufacturers, what are the typical volumes purchased annually or requested in future years by individual companies?

Aspect	This study			Tuomisto et al. (2022)			Humbird (2021)	
	Low medium	Mid medium	High medium	CMB	CMB128	CMC	Wild-type catabolism	Enhanced catabolism
Amino acids (g/kg CM)	200	283	400	448	197	196	453	388
Sugars (g/kg CM)	320	400	500	1270	557	557	816	360
Dry mass	20%–30%	20%–30%	20%–30%	30%	30%	30%	30%	30%
Protein content	18%–25%	18%–25%	18%–25%	20%	20%	20%	21%	21%

Table D.9 – Comparison of amino acids and glucose mass balance between this study and other, recent studies (data from other studies recalculated to g/kg CM using publicly available information)

Previously published research (above, Sinke et al 2023) suggests that between ~200-450 grams of total amino acids would be required per kg of cultivated meat.

How do these numbers align with your understanding of current or targeted bioconversion efficiencies for the cultivated meat sector?

Which amino acids are most likely to have a supply bottleneck based on current production scales and your understanding of future requirements in cell culture media? Could the rapid growth of cultivated meat or competition from biopharma/biomedical industries quickly outstrip the supply of certain amino acids? Do you have a specific reference that you believe accurately represents the current production volumes and market sizes for amino acids?

Which amino acids are used in the highest quantity or do you expect the highest demand for in cell culture media for cultivated meat?

To what extent is infrastructure and capacity a limiting factor to meeting demand?

Which amino acid suppliers do you purchase from? Or which amino acid manufacturers currently supply the cell culture media market to your knowledge?

What do you think cultivated meat companies need most from amino acid or hydrolysate suppliers over the next 5–10 years to help you reach scale?

Can you generally describe how the supply chain works for sourcing amino acids for cell culture media? What are the primary considerations when choosing a supplier? What ingredient qualifications are of most concern for sourcing amino acids? Are there any specific CoA items of most interest?

Feed vs. food grade questions

Do you currently sell amino acids (as standalone or in pre-mixed formulas) directly to cultivated meat manufacturers? If so, what grade — pharma-grade, food-grade, and/or feed-grade?

Have you ever ordered and tested food- or feed-grade amino acids purchased on aggregated supplier sites such as Alibaba, Made-in-China, Bulksupplements, or similar providers? If so, how did these perform?

Our understanding is that feed-grade amino acids may pose performance challenges in cell culture due to higher variability of batches and overall product specifications. Do you have experience testing feed-grade amino acids in cell culture? What are the primary contaminants or qualifications of most concern that may impact process performance? What are the primary controls to mitigate performance risk for feed-grade amino acids that would ensure they consistently perform well in cultivated meat applications?

Our understanding is that feed-grade amino acids may pose regulatory challenges if used in cultivated meat production because they require fewer or different specifications than food-grade amino acids, particularly around heavy metal burden or other contaminants (e.g., aflatoxins). Is this a correct understanding? What other regulatory concerns are you aware of regarding feed-grade amino acids intended to be used in the cultivated meat industry? What are the primary controls to mitigate safety or regulatory risks related to heavy metals or other contaminants in feed-grade amino acids for use in cultivated meat? Are you aware of certain regions or jurisdictions that would only permit food-grade (or higher quality) amino acids in cultivated meat production due to regulatory reasons?

To what degree are these regulatory and performance challenges and controls shared with food-grade amino acids?

Would it be desirable to develop standardized “cultivated meat-grade” specifications that balance aspects of current food- and feed-grade specs to achieve the cost, performance, and safety requirements for the cultivated meat sector?

If you have submitted a safety dossier for regulatory approval, did your process use pharma-grade, food-grade, feed-grade amino acids, or combinations of these? Are you planning to have your future regulatory submissions replace pharma-grade amino acids with food- or feed-grade amino acids?

Hydrolysate questions

Do you believe that hydrolysates will need to be used in media to reach price parity with conventional meat products? Why or why not?

What raw materials do you believe would be good candidates for testing but no commercial option currently exists (e.g., microbial biomass, microalgae, macroalgae, other crops)?

Is your selection of raw materials guided by an understanding of the metabolic demands and amino acid utilization rates of your specific cell line?

Are you able to share any real price quotes for bulk purchase of hydrolysates in the range of 1 to 100 kg or 100 kg to 1 tonne? To what extent is price variability driven by raw materials? To what extent is price variability driven by hydrolysis method (e.g., enzymatic, heat/acid, other)?

What is the predominant method of hydrolysis (i.e., enzymatic, heat/acid, other) that you employ?

How are these methods selected and optimized? Do they vary based on the raw material?

Can you generally describe how the supply chain works for producing hydrolysates for cell culture media? What are the primary considerations when choosing a raw material supplier? What does the QA/QC process look like for manufacturing hydrolysates (i.e., what methods/unit operations are performed)? What ingredient qualifications are of most concern for using hydrolysates in cell culture media? Are there any specific CoA items of most interest?

Do you currently produce pharma-grade, food-grade, and feed-grade hydrolysates? If so, what raw materials do you currently manufacture (e.g., yeast, soy, cottonseed)?

Do you (or your customers) select raw materials or optimize hydrolysis methods based on the specific nutritional needs of particular cell lines? If so, what informs that process? What additional raw materials are you exploring for commercialization (e.g., microbial biomass, microalgae, macroalgae, other crops)?

At what percentage or concentration do you recommend using hydrolysates in media? What technical issues are most important to address for hydrolysates (e.g., variability, solubility, anti-nutritional factors, production method, raw material source, other impurities)? Do you monitor or control for toxins (e.g., endotoxin, aflatoxin), heavy metals, or other potential contaminants in your hydrolysates? If so, how are these mitigated, and how do they differ by grade? Does performance or consistency vary between pharma-, food-, or feed-grade hydrolysates for sensitive applications like cell culture media?

What are the primary reasons your customers are pursuing the use of hydrolysates in media (e.g., cost, amino acid supply constraints, etc)? To what degree could media cost be lowered if hydrolysates were used as a nutritional replacement for amino acids (and other) components?