THE MOLECULE MANIFESTO

FOUR PRIORITY MOLECULE FAMILIES TO UNLOCK INDUSTRIAL BIOTECH SCALE

Advanced Biotech for Sustainability

CONTENTS

PREFACE

The first Advanced Biotech for Sustainability (AB4S) report published in 2025 asked a big question: *How large is the economic and environmental opportunity in advanced biotechnology?*

The answer reframed how the industry thinks about deployment.

Report 1 mapped the sustainability potential of bio-based molecules in unprecedented depth and distilled the path to scale into three actionable principles: bring deep tech into low-tech infrastructure, minimize variables early, and standardize wherever possible.

The trillion-dollar market opportunity by 2040 was the headline that traveled, but the substance that drove the conversation was what deployment would actually require.

This report addresses a harder question that followed, the one executives and investors kept asking:

Where, specifically, should we start?

This report answers that question.

The AB4S coalition was formed on a simple premise: industrial biotechnology would not scale through another consultant-led study. It required the people who build, buy, invest in, and regulate these molecules to sit at the same table. Incumbents, startups, facilitators, and analytical partners needed to work from shared operational reality rather than theoretical potential. That combination of stakeholders, working from practice rather than theory, is what makes this coalition different from previous efforts. It is also what gives its conclusions weight.

The coalition's members span Europe and North America. This report analyzes the global competitive landscape, including China's rapidly expanding biomanufacturing capacity, but its actionable recommendations are primarily directed at industry and policy stakeholders in regions where the coalition's members operate and where coordinated action can begin immediately.

After screening more than 300 molecules across 40 chemical families, conducting over 30 expert interviews, and pressure-testing conclusions at a full-day industry workshop, the AB4S coalition identified four priority molecule families—terpenes, peptides, non-catalytic proteins, and hydroxy acids. Not the only candidates, but the ones the coalition judged to be both the most compelling near-term opportunities and the most representative of the scaling challenges ahead, and whose infrastructure opens the door to many more.

The *Molecule Manifesto* is not a research paper.

It is a deployment framework written by the stakeholders who will build, use, and invest in these molecules. It is written for the decision-makers who will determine whether bio-based production scales or stalls: industry executives evaluating new supply chains and product portfolios, investors assessing where to deploy patient capital, policymakers shaping the regulatory and financing environment, and technology developers choosing which platforms to build. It translates twenty years of sector-level learning into a focused, molecule-specific roadmap, designed not for biotechnology specialists, but for anyone with a stake in the industries that biotechnology will reshape.

The authors of this report are senior leaders across the biotechnology and chemistry value chain, and entrepreneurs with direct operational stakes in the markets described here.

The AB4S coalition does not invent technologies or operate production facilities. Our ambition is to align fragmented demand, connect stakeholders across the whole value chain, and de-risk capital commitments that turn laboratory potential into industrial reality.

The first report made the case for advanced biotechnology. This second report names the molecules, identifies the markets and end-users, and lays out the infrastructure, capital, and coordination required to reach commercial scale. It is deliberately specific because specificity is what has been missing. The bioeconomy does not need another vision statement. It needs end-to-end concrete commitments, shared infrastructure, and coordinated execution.

Each commitment makes the next one easier. Every offtake agreement signed, every pilot facility funded, and every qualification cycle shortened reduces the cost of going first. The molecules are ready. The market signals are clear. What remains is the collective and coordinated decision to act.

The conclusions and recommendations are the coalition’s own. The report is backed by knowledge and analytical support from McKinsey & Company. For further information, see ab4s.org.

Sincerely,

The AB4S Coalition

ACKNOWLEDGEMENTS

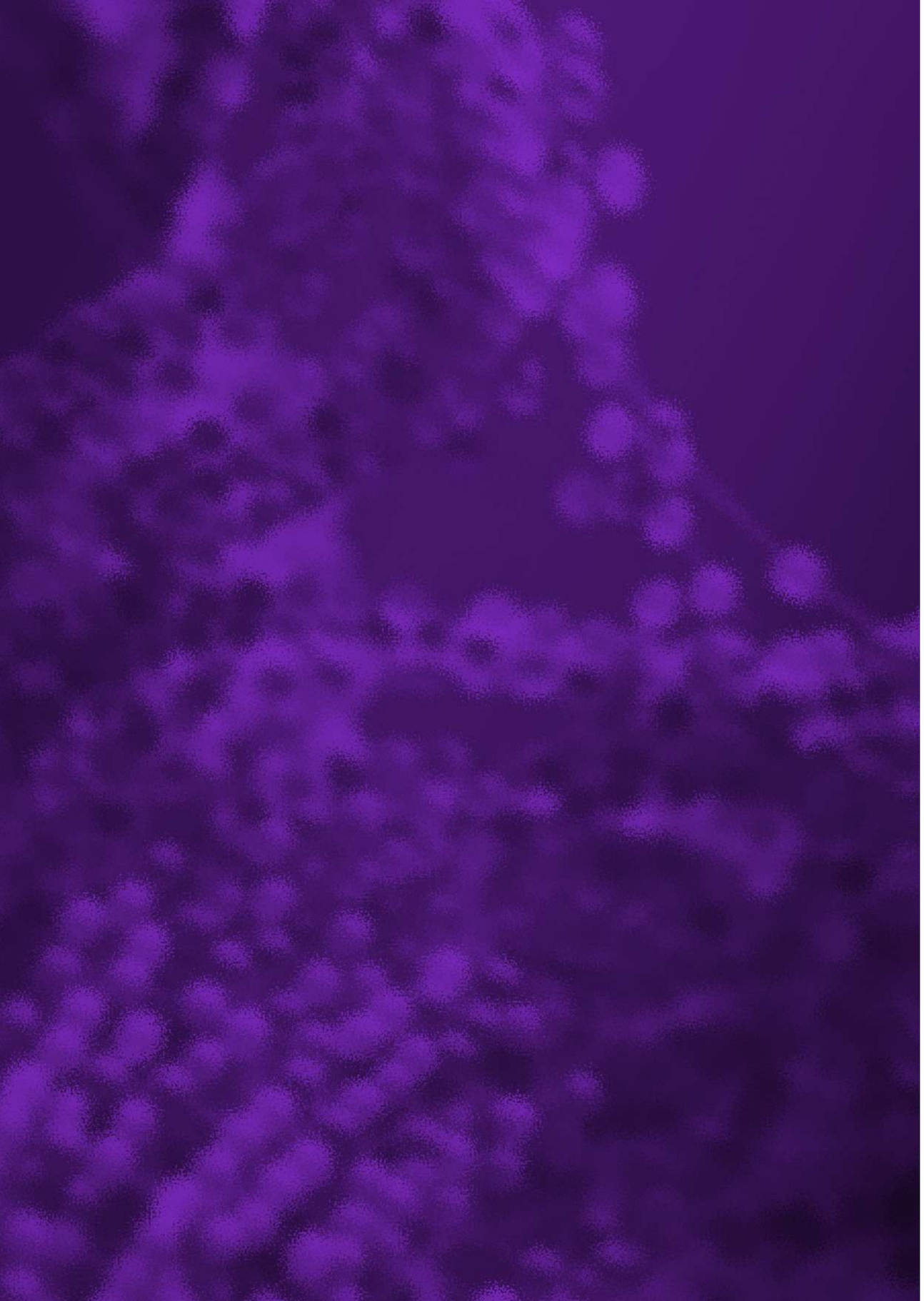
The research and analysis were led by Massimo Portincaso and Paul Hill from Arsenale Bioyards; Olivier Rolland and Fabien Deswarte from L'Oréal; Christoph Kobler and Stefan Pelzer from Evonik; Eva Wilke from BASF; Danielle Cusumano, Majdi Najah, Ildar Nisamedtinov, and Kevin Wenger from Lallemand; Katherine Foster and Lorena Savani from EIT Food; Emanuele Monza, Luba Protopopova, Katy Svennas, Stef van Grieken, and Jarred Yacob from Cradle; with Anna Littmann, Mark Patel, Pol van der Pluijm, Kevin Ren, Anna Stepien, and Tom Brennan from McKinsey & Company.

Neil Renninger contributed as lead author, bringing direct operational experience from building and scaling biomanufacturing companies.

The coalition conducted more than 30 expert interviews between October and December 2025, spanning technology developers, CPG and chemical company leaders, investors, and academic researchers. These conversations shaped the molecule prioritization, validated technical and commercial assumptions, and informed the deployment recommendations throughout this report.

A full-day workshop held on November 25, 2025, at L'Oréal's premises in Saint-Ouen, France, brought together coalition members and invited experts to validate the four priority molecule groups, pressure-test findings and commercial assumptions, and develop initial action plans for each molecule family. The insights from that session are woven throughout this report.

Evonik coordinated general coalition activities. Arsenale Bioyards coordinated coalition reporting. L'Oréal provided strategic guidance throughout the development process. McKinsey & Company provided knowledge and analytical support. Messaginglab wrote the report.



1: EXECUTIVE SUMMARY

The first AB4S report quantified the economic and environmental potential of advanced biotechnology, up to $1.1 trillion[1] in market value by 2040 across food, chemicals, personal care, and fuels. The report also demonstrated that bio-based production could abate 3–4 metric gigatons of CO_2-equivalent annually by 2040, roughly triple global aviation emissions, while reducing land and water use at scale. Finally, it made the case for prioritization, de-risking scale-up, and accelerating cost reduction.

This second report answers the next question:

Where should we start?

After evaluating more than 300 molecules across 40 chemical families, the AB4S coalition has identified four priority molecule families that represent the most compelling near-term opportunities for bio-based production at scale:

- terpenes, the foundation of $7–12 billion in global supply chains spanning rubber, cosmetics, flavors, and agriculture;
- peptides, high-performance molecules addressing regulatory-driven reformulation across food, crop protection, and personal care;
- non-catalytic proteins, functional ingredients for infant nutrition, sports nutrition, and food manufacturing facing regular supply disruptions; and
- hydroxy acids, building blocks for some of the world's largest chemical value chains including acrylates, polymers, and solvents.

Produced via biotechnology, these four families share a critical characteristic: they can offer advantages in specific applications that

[1] All figures in US dollars unless otherwise noted.

conventional production routes cannot match, whether in performance, supply security, regulatory compliance, sustainability, or cost competitiveness[2].

They are not the only candidates. They are the ones this coalition judged to be the most actionable now and the most aligned to foundational trends in health, energy, food, and consumer products that will outlast any single market cycle. Molecules evaluated but not prioritized, including enzymatic proteins (a mature market with established incumbents), are addressed in the Methodology Section.

Advanced biotechnology has struggled to scale for twenty years. Focus is overdue.

Advanced biotechnology has struggled to scale for twenty years. Focus is overdue.

This report provides the deployment frame for these priorities, explaining why these molecules, why now, and what it will take to move from pilot to commercial scale.

What follows is built for commercial and strategic decision-making, not technical review. The analysis is grounded in science but oriented toward deployment, toward the capital, infrastructure, and coordination decisions that will determine how quickly these molecules reach industrial scale.

This report arrives at a moment when artificial intelligence (AI), geopolitical competition, resource scarcity, and the drive for supply chain sovereignty are converging on the same conclusion: nations and companies that control bio-based production will hold structural advantages in food security, materials independence, and economic resilience. China is building that capacity now, with state-backed plans to scale biomanufacturing across 43 companies by 2027. The window for coordinated action by Western industry and governments is narrowing. The ambition of this effort is global impact, not incremental progress.

The Case for Bio-Based Production

The conventional routes for producing many of today's industrial molecules face mounting pressure.

- **Supply chain fragility, localization, and resilience**. Global supply chains for specialty chemicals, flavors and fragrances, and functional ingredients have proven vulnerable to disruptions from pandemic-driven logistics failures, and geopolitical shocks and climate-driven agricultural volatility. Petrochemical feedstocks remain subject to price swings and trade tensions. *Bio-based production can reduce dependence on petrochemical and extractive supply chains, and biomanufacturing can be sited near feedstock sources or end-markets. As governments prioritize domestic production capacity for strategic materials, bio-based manufacturing offers a path toward reduced import dependence.*
- **Sustainability imperatives.** The first AB4S report estimated that bio-based production could abate 3–4 metric gigatons of CO_2-equivalent annually by 2040, roughly triple global aviation emissions, while freeing up to 4 million square kilometers of land. As of early 2026, 10,000 companies have validated science-based emissions reduction targets through the Science Based Targets initiative[3]. Mandatory Scope 3 target-setting (defining a quantitative greenhouse gas reduction goal specifically for a company's value-chain emissions, both upstream and downstream, usually as part of an overall climate or net-zero strategy) is pushing many large buyers to embed emissions reductions into supplier selection and procurement processes. *Bio-based molecules are not a green premium. They are a compliance necessity.*
- **Regulatory changes are creating a demand-pull for bio-based molecules that conventional routes cannot satisfy.** Multiple jurisdictions, the EU, several U.S. states, and parts of Asia are moving toward strict limits or bans on intentionally added PFAS (or "forever chemicals") in cosmetics, prompting broad reformulation and urgent demand for alternatives that conventional chemistry struggles to deliver. *Regulation is not just removing incumbents. It is actively creating markets for bio-based alternatives.*
- **Performance limitations.** Chemical synthesis produces racemic mixtures. Biology produces stereospecific molecules. Chemical routes struggle with complex structures. Fermentation handles them routinely. *For many molecules where chirality, bioactivity, or multifunctionality are critical, bio-based routes offer advantages that conventional petro-chemical synthesis struggles to match, particularly at high stereochemical complexity.*
- **Cost trajectory.** Bio-based production costs follow learning curves. Strain engineering, process optimization, and scale economics have driven fermentation costs down by orders of magnitude, as demonstrated over recent decades with amino acids, citric acid, and industrial enzymes. Petrochemical production, by contrast, benefits from over a century of process optimization, trillions in accumulated infrastructure investment, and feedstock costs that, while volatile, remain structurally low. But those costs are structurally tied to oil and gas markets. Where bio-based routes face higher costs today, the trajectory is toward convergence, and the molecules in this report were selected in part because that convergence is already visible.

Four Priority Molecule Families

AB4S evaluated more than 300 individual molecules against four criteria: market size sufficient to justify investment (>$1.5 billion by 2030), demonstrated corporate interest and demand pull, a credible path to cost competitiveness, and technological readiness for near-term scale-up.[4] *Four families met all thresholds.*

Terpenes: The Market-Ready Opportunity

Terpenes and terpenoids, including monoterpenes like linalool and limonene, sesquiterpenes like patchoulol and valencene (which are already produced commercially), and the C5 building block isoprene, represent a $ 7–12B market and the fastest path to commercial deployment. Today, many of these molecules are produced commercially through extraction from plant material, a process constrained by agricultural land use, seasonal variability, and inconsistent quality. Botanical extraction is concentrated in climate-vulnerable equatorial regions, creating trade dependencies for importing nations. Natural rubber alone is a strategic material for transportation and defense.

The fragrance and flavor industry already accepts bio-sourced terpenes at premium prices[5]. Platform economics allow a single fermentation host and process to produce multiple products, spreading development costs across a portfolio. Proven platform pathways have established customer acceptance, and a near-term bio-production timeline for high-value terpenes makes this class of molecules attractive. The challenge is sequencing investment across a large and diverse molecule family to maximize early wins while building toward higher-volume opportunities. Specialty flavors and fragrances are near-term; platform molecules like isoprene are a five-to-ten-year horizon.

[2] See Methodology for molecules evaluated but not prioritized, including enzymatic proteins (mature market with established incumbents)..
[3] Science Based Targets Initiative. Corporate climate action momentum builds as SBTi reaches 10,000 companies with validated targets. Press release. 22 January 2026. https://sciencebasedtargets.org/news/sbti-celebrates-10000-company-validations

[4] See Methodology section below.
[5] Bomgardner M. Why the flavor and fragrance industry is embracing biotechnology. C&EN. 2 February 2021. https://cen.acs.org/business/specialty-chemicals/flavor-fragrance-industry-embracing-biotechnology/99/i5

Peptides: The Platform Long Game

The commercial success of GLP-1 peptide therapeutics has demonstrated what the peptide class is capable of: precise biological activity, strong market acceptance, and platform economics that allow a single production infrastructure to serve multiple products. The same logic applies beyond the pharmaceutical industry.

Bioactive peptides span applications from cosmetics and personal care to agriculture and food, with pigment-modulating actives, antimicrobial preservatives, and biopesticides, to name a few.

The value proposition for these molecules lies in their multifunctionality: a single peptide can deliver adhesion, antimicrobial activity, and sensory properties simultaneously. Regulations phasing out traditional chemicals are creating urgent demand in cosmetics. At the same time, the maturation of recombinant production platforms and growing regulatory acceptance for peptide-based biopesticides, which can ensure food security, make this class of molecules attractive. Today, high-value cosmetics peptides are near-term; agricultural and food applications are medium-term.

Non-Catalytic Proteins: The Functional Future

The industrial enzyme industry has already proven that proteins can be produced via fermentation at commercial scale and at competitive costs. Non-catalytic proteins represent the next horizon, extending that platform logic to molecules that deliver function through structure and bioactivity rather than catalysis. Functional proteins, including dairy proteins (lactoferrin, β-lactoglobulin), egg proteins (ovalbumin, ovomucin), and sweet proteins (brazzein, thaumatin), deliver performance through physical and biological function: foaming, gelling, emulsification, sweetness, and bioactivity. Structural proteins such as collagen and silk are already commercialized in cosmetics.

Precision fermentation produces these proteins without animal agriculture, reducing supply chain volatility and enabling new functionality. Demand is driven by chronic supply constraints for lactoferrin, protein supply volatility from avian flu-affected eggs—the kind of concentrated production risk that triggered the 2022 US infant formula crisis—and sports nutrition brands pursuing differentiation. However, cost pressure remains significant: several precision fermentation protein companies have struggled to reach sustainable unit economics. β-lactoglobulin is near-term; casein, egg, and sweet proteins are medium-term; and structural proteins beyond cosmetics are longer-term. But the size of the addressable market and the strategic vulnerability of conventional supply chains make non-catalytic proteins one of the highest-potential families in this report.

Hydroxy Acids: The Brownfield Integration Investment

Hydroxy acids offer the clearest path to large-scale bio-based volumes because they integrate into existing chemical infrastructure rather than requiring purpose-built biomanufacturing facilities. Citric and lactic acids, multi-billion-dollar markets with established bio-routes, already prove that fermentation works at commodity scale. One compelling near-term opportunity is 3-HP, which converts to acrylic acid, a 7-million-ton market serving superabsorbent polymers, coatings, and adhesives.

Unlike fragmented specialty markets, acrylic acid and its derivatives sit deep in manufacturing value chains with multiple buyers: major diaper and absorbent product manufacturers can baseload a plant with a single offtake, and sustainability claims resonate in consumer-facing applications. Domestic bio-based production reduces petrochemical import dependence and creates regional manufacturing jobs. The challenge is cost parity: commodity-scale volumes require significant capital, and petrochemical incumbents set a demanding price floor. This is not a performance play: It is a volume play where success depends on scale economics, feedstock costs, and demand aggregation.

> Bioactive peptides span applications from cosmetics and personal care to agriculture and food, with pigment-modulating actives, antimicrobial preservatives, and biopesticides

Positioning the Opportunity

The four molecule families occupy different positions along two key dimensions: time to commercial scale and infrastructure requirements.

Specialty terpenes can enter the market by adding purpose-built purification capacity to existing fermentation facilities, keeping initial capital requirements manageable. Scaling to platform volumes across the terpene family will eventually require dedicated multipurpose facilities, but near-term market readiness and platform economics reduce the risk of that investment.

Peptides require new dedicated production capacity and extended timelines for regulatory approval and commercialization (though existing CDMO and enzyme manufacturing infrastructure can serve early-stage needs). The near-term opportunity lies in high-value cosmetics actives driven by PFAS phase-outs; agricultural biopesticides are emerging now with early commercial products already generating millions in revenue, and broader food applications are medium-term.

Non-catalytic proteins also require new dedicated capacity but represent the largest addressable market of the four families. Significant application development is needed to identify and valorize performance advantages that differ from incumbent ingredients. Chronic supply constraints, protein supply volatility, and brands pursuing differentiation drive demand.

> Hydroxy acids integrate into existing chemical infrastructure

Hydroxy acids integrate into existing chemical infrastructure, but commodity-scale volumes still require substantial capital, and the path to cost parity with petrochemical incumbents is the longest of the four families.

Key Insights from Prioritization

The AB4S coalition's analysis surfaced several findings that shape deployment strategy.

- **Hybrid routes accelerate scale.** Producing bio-based intermediates via fermentation, then finishing them through established chemistry, can enable faster cost competitiveness than pure biological routes. The 3-HP-to-acrylate pathway exemplifies this logic. Hybrid approaches leverage existing chemical infrastructure and supply chains while capturing biology's advantages in the synthesis step.
- **Downstream processing is the primary cost driver, but not universally.** For high-value, low-volume molecules (peptides, specialty proteins, fragrance terpenes), DSP accounts for 20–40% of operating costs and heavily influences scale-up economics[6]: It is the critical cost driver in these segments. For commodity-scale molecules (hydroxy acids, isoprene), feedstock and bioconversion costs are equally or more important. Sweeping claims about a single bottleneck obscure

[6] Straathof A.J.J. The proportion of downstream costs in fermentative production processes. Comprehensive Biotechnology. Vol 2, 2011 pages 811-814. https://www.sciencedirect.com/science/chapter/referencework/abs/pii/B978008088504900492X?via%3Dihub

the molecule-specific analysis that deployment decisions require.

- **Regulation limits adoption.** New safety and environmental regulations are eliminating categories of performance chemicals, creating urgent demand for alternatives. Yet approval pathways for bio-based replacements (Novel Foods in Europe, Generally Recognized as Safe (GRAS) in the U.S., biopesticide registration) vary dramatically by geography, and slow-moving regulatory processes delay adoption.
- **Brownfield vs. multipurpose is the infrastructure fork.** Terpenes, peptides, and proteins require new multipurpose facilities designed for flexibility across products and can compete on performance differentiation. Hydroxy acids can integrate with existing chemical facilities, but commodity-scale production demands substantial capital and patient timelines to reach cost competitiveness. Both tracks are needed.
- **Demand validation must precede infrastructure investment.** The lesson from past biotech scale-up failures in the US and EU is consistent: building capacity without confirmed demand leads to stranded assets. China is following a different playbook: state-backed industrial policy is expanding bio-manufacturing capacity, particularly in large-scale fermentation, and the country now accounts for 70% of biofermentation products.[7,8] This creates both competitive pressure and a narrowing window for Western players to establish scale. Binding offtake agreements, co-development partnerships, and demand aggregation across buyers must come before major capital deployment.

From Analysis to Action

The first AB4S report established the potential of advanced biotechnology. This report identifies where that potential is most actionable. Four molecule families—terpenes, peptides, non-catalytic proteins, and hydroxy acids—offer credible paths to scale based on market demand, technological readiness, and deployment economics.

The molecules are ready. The market signals are clear. The infrastructure models are understood. What remains is coordinated execution: demand commitments that justify capital, capital structures that match industrial timelines, regulatory pathways that enable market access, and collaboration models that reduce the cost of going first.

The coalition's role is to raise awareness and catalyze action across stakeholders to accelerate the transition from pilot to commercial scale, turning the bio-based economy's promise into production.

[7] Sedzro T. Positioning for Growth: Navigating China's Biomanufacturing Industry. China Briefing. 2 January 2026. https://www.china-briefing.com/news/chinas-biomanufacturing-industry-opportunities/
[8] Lorgilyn. China's Bio-Manufacturing Sector Shows Strong Growth During 2021–2025. 22 December 2025. SupplyChainReport.org. https://supplychainreport.org/chinas-bio-manufacturing-sector-shows-strong-growth-during-2021-2025/

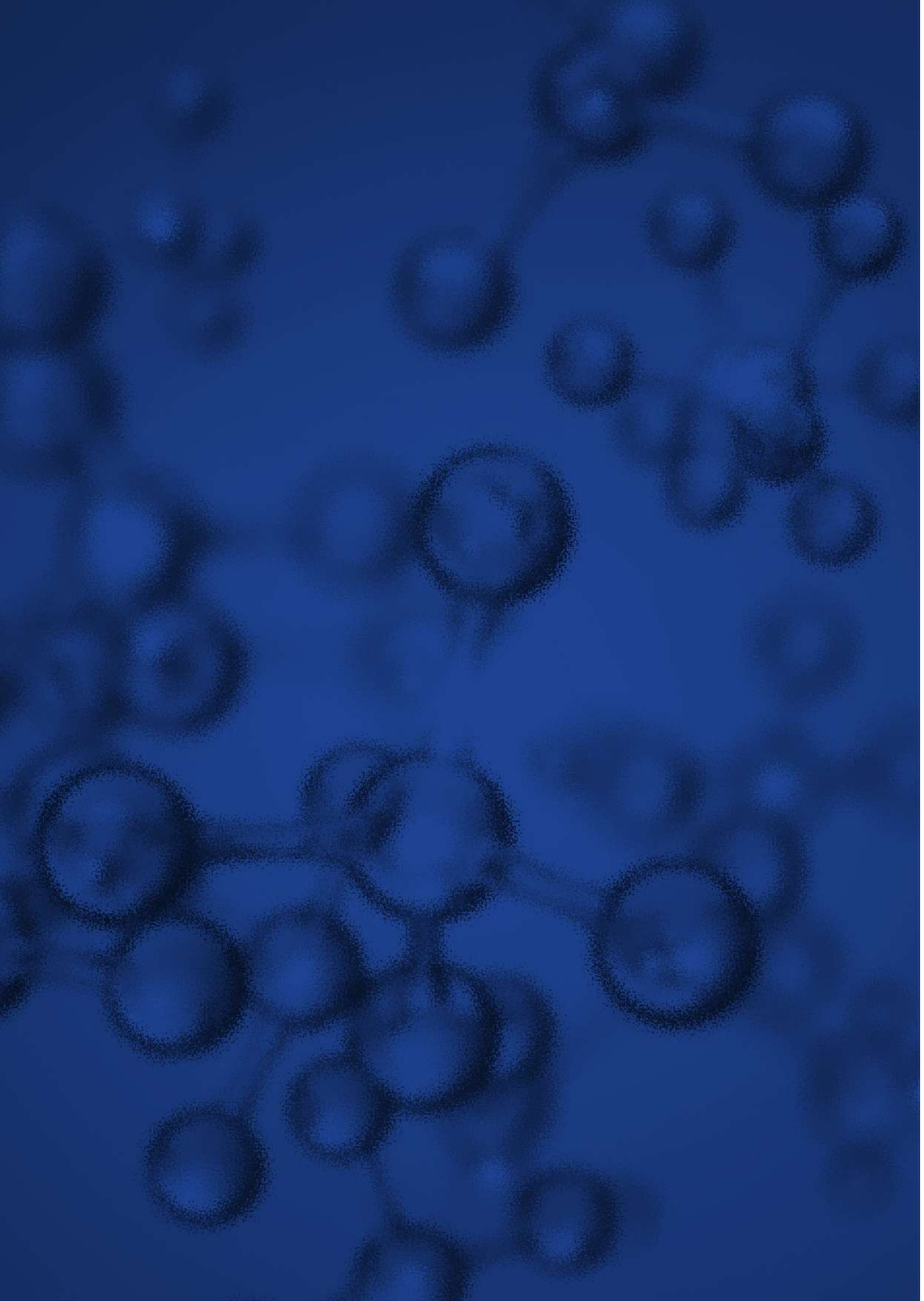
PRIORITY ACTIONS

For CPG Brands and Chemical Companies: Commit early. Binding offtake agreements de-risk capital investment and unlock scale. Co-development partnerships compress qualification timelines and ensure molecules meet application requirements. Validate new molecules in existing biomanufacturing facilities before committing to dedicated FOAK capacity: early proof points in current infrastructure reduce risk and accelerate the path to scale. Elevate sourcing decisions from procurement to C-level strategy.

For Investors: Match capital to risk profile. Industrial biomanufacturing sits between venture and infrastructure risk. Typically too long for traditional VC, too uncertain for project finance. Blended structures that combine equity for innovation with debt as well as strategic capital for scale can bridge this gap. Fund first-of-a-kind (FOAK) and second-of-a-kind (SOAK) facilities through structures that reflect this hybrid risk profile.

For Policymakers: Streamline regulatory pathways. Support FOAK infrastructure through loan guarantees and tax incentives. Coordinate national biomanufacturing strategies to match China's deliberate industrial policy. Invest in workforce development.

For the Coalition: Orchestrate, don't invent. Technical innovations exist. The coalition's role is coordination: aligning fragmented demand, connecting technology developers with key strategic customers, accelerating qualification through shared infrastructure, and de-risking capital deployment through demand aggregation. Each binding commitment makes the next one easier.



2: FROM INFRASTRUCTURE TO MOLECULES

What Report 1 Established

The first AB4S report examined why advanced biotechnology has not yet reached its full potential. It identified four dimensions of de-risking required for industrial biotechnology to scale: **technical, commercial, financing, and capabilities.**

In the pharmaceutical sector, value is secured early through patent-protected discovery and clinical validation. In contrast, for many industrial molecules, value is traditionally realized only at commercial scale.

However, the coalition identifies a paradigm shift for high-complexity molecules like peptides and proteins: where performance is radically differentiated (e.g., bioactive ingredients), value is captured at the point of validation, not at commercial scale. While lab-scale innovation creates the foundation, the transition to high-performance formulations and industrial-scale production at competitive cost is where the coalition sees the ultimate realization of market value.

Report 1 articulated three enabling concepts for accelerating deployment.

- **Reduction of variables:** minimize the variety of approaches across business and technology to concentrate resources on fewer, more promising pathways.
- **Standardization:** create uniformity across processes, tools, and measurement approaches to streamline development and scaling.
- **Shifting from high-tech development to low-tech deployment:** leverage existing cost-effective and repeatable technologies to kick-start markets, don't invent new production systems for each product.

These insights remain foundational. But infrastructure alone does not create markets.

The question this report addresses: *Infrastructure for what?*

Why Infrastructure-First Approaches Struggled

The 2010s offered hard lessons in what happens when biotechnology attempts to scale without demand-side validation.

"Drop-in" proved harder than advertised. BioAmber invested in bio-based succinic acid, expecting straightforward substitution, but downstream derivatives hadn't matured, and reformulation required full supply chain participation that the company couldn't orchestrate[9] [10] [11].

High-tech processing eroded feedstock advantages. Plant-based meats like Impossible and Beyond still cost more than animal meat largely because of higher processing and ingredient costs, even though they use inexpensive crops as feedstocks[12, 13, 14].

Cost parity with fossil-based commodities remained out of reach. Too often, targets were commodity molecules where petrochemical incumbents had decades of process optimization and rock-bottom prices that bio-based routes could not match.

> The pattern was consistent: supply-side innovation was occurring without anchored demand.

The common thread: Companies built capacity based on assumptions that didn't survive contact with market reality, whether that meant discovering that customers wouldn't reformulate, that processing costs swamped feedstock savings, or that the path to cost competitiveness was far longer than projected.

The pattern was consistent: supply-side innovation was occurring without anchored demand.

Companies targeted commodity markets—fuels and bulk chemicals—where achieving petrochemical cost parity proved nearly impossible. Plants were built before technology was mature enough to deliver at target economics. Investors funded scale-up without validated offtake at prices that worked. Costs stayed high because volumes stayed low.

The bioeconomy's "valley of death" reflects a chicken-and-egg dynamic: without volume, cost structures cannot improve; without competitive costs, market pull cannot develop. Technology challenges were real, but so was market coordination failure, and neither could be solved in isolation.

This report emphasizes demand validation because project-financed plants with clear offtakes represent the end state in market economies. But we are in a transitional phase where building the multipurpose, flexible, strategically located infrastructure remains essential. China's subsidized capacity buildout adds urgency. The window for Western players to establish scale is narrowing.

Why Molecule-Led Planning Works

Markets do not scale through generic infrastructure: They scale through specific applications with specific performance requirements, supply chain integrations, and regulatory pathways. A terpene platform succeeds not because fermentation works but because a flavor house needs a consistent patchoulol supply and pays for it. A hydroxy acid plant gets built not because 3-HP fermentation is elegant, but because a global consumer packaged goods company wants bio-based superabsorbent polymers for diapers and underwrites the offtake.

Molecule-led planning inverts the development sequence. It begins with demand validation: Which molecules have customers ready to buy at prices that work?

It then works backward to the infrastructure required: Can existing facilities be leveraged, or must new capacity be built?

This approach aligns capital with market pull rather than hoping markets will materialize for whatever technology produces.

Advances in AI and computational biology are making molecule-led planning more actionable than it was even five years ago, compressing the timeline from target identification to strain optimization and accelerating the market-readiness assessments that determine where to invest.

The four molecule families in this report were selected precisely because they exhibit validated demand signals. Terpenes have established buyers in the flavor and fragrance markets. Hydroxy acids have attracted interest from major consumer packaged goods (CPG) companies. Peptides address regulatory-driven demand in cosmetics and agriculture. Non-catalytic proteins serve infant formula and sports nutrition markets already accustomed to premium pricing for functional ingredients.

Selection Criteria

The molecule groups were prioritized through quantitative and qualitative assessment, combining market data with more than thirty expert interviews and validation at a November 2025 workshop. Insights throughout this report reflect synthesis across these three inputs, and recommendations represent coalition conclusions rather than any single source.

Quantitative thresholds ensured a focus on molecules with sufficient scale to justify investment:

- Total market size in 2030 exceeding $1.5 billion,
- Biotech addressable market potential exceeding $1 billion, and
- Unit prices above $3 per kilogram, a floor to exclude ultra-low-value commodities where biotech's early-stage cost premium can still yield healthy margins[15].

Qualitative assessment addressed factors that quantitative screening cannot capture:

- Performance advantages or drop-in compatibility that justify adoption even before full cost parity,
- Corporate interest and consumer pull indicating likelihood of partnerships, offtake, and adoption,
- Technological readiness across the pre-pilot to commercial spectrum, and
- A credible path to cost competitiveness against petrochemical or extractive incumbents.

For each molecule family, the critical questions were:

- Why is biology a unique way to make this happen?
- What does precision fermentation offer that incumbents cannot replicate, whether supply resilience, stereochemical precision, access to novel structures, reduced process hazards, increased sustainability, or design freedom to engineer performance beyond what nature provides?

[9] Lee, S. T., et al. "Empirical analysis of large-scale bio-succinic acid production: A Techno-Economic and Innovation Perspective." Renewable and Sustainable Energy Reviews. 2021. https://ui.adsabs.harvard.edu/abs/2021RSERv.13710587L/abstract.
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[15] See Methodology section below.

Two Deployment Tracks

The four priority molecule families divide into two distinct deployment tracks with different infrastructure requirements, partnership models, and capital strategies.

1. **Molecules requiring new multipurpose production facilities** follow different economics than brownfield-compatible molecules. Peptides and non-catalytic proteins require purpose-built fermentation and downstream processing capacity, justified by premium pricing through performance differentiation, but their capital requirements are higher and their timelines are longer. Terpenes present a mixed picture: specialty terpenes (patchoulol, nootkatone) compete on performance and scarcity, commanding premium prices that can support new facility investment, while platform terpenes (isoprene, farnesene) are drop-in molecules competing on cost, where contract manufacturing and existing capacity may provide a bridge to scale. Platform terpenes share some characteristics with brownfield-compatible molecules, competing on cost rather than performance, but their downstream processing differs enough that they are not direct bolt-ons to chemical infrastructure.
2. **Brownfield-compatible molecules** can integrate with existing chemical value chains rather than requiring new or greenfield biomanufacturing facilities. Hydroxy acids are the clearest example: citric and lactic acid prove that fermentation works at commodity scale, and novel molecules like 3-HP can bolt onto established chemical infrastructure. But brownfield compatibility does not mean easy. The challenge is achieving cost parity with entrenched petrochemical incumbents producing at rock-bottom prices. The success of these molecules requires economies of scale, reliable low-cost feedstock, and demand aggregation sufficient to baseload plants.

Success depends on demonstrating market-valued performance, securing co-development partnerships with downstream users, and deploying capital structures that accommodate longer commercialization cycles.

Regional Considerations

Infrastructure geography matters. Fermentation capacity is not evenly distributed globally, and energy costs, feedstock availability, and regulatory environments vary significantly by region.

China has announced plans to build pilot biomanufacturing plants across 43 companies by 2027[16]. This is likely the largest coordinated biomanufacturing scale-up effort in the world. Chinese biomanufacturers benefit from lower labor and energy costs, subsidized infrastructure, and government support. Their strategy follows a familiar playbook: concentrate capital and policy support in critical upstream technology, scale faster than global competitors, and lock in cost and supply-chain advantages over time. For newer biomanufactured products, labor costs may rival or exceed energy as a driver of facility siting, an advantage that compounds China's position beyond cheap power alone.

The European Union is moving to scale its bioeconomy through coordinated industrial policy under the Net-Zero Industry Act[17] and its recently released Bioeconomy Strategy[18]. European policymakers are focused on accelerating deployment from lab to market, expanding pilot and demonstration-scale capacity, streamlining regulation, mobilizing blended public-private financing, and securing biomass and feedstock supply chains across Member States.

The United States leads in frontier biotechnology and discovery but faces coordination challenges in translating lab breakthroughs to commercial production. Initiatives like BioMADE and the Distributed Bioindustrial Manufacturing Program are strengthening domestic bioindustrial capacity. Still, biomanufacturing has not yet achieved the sustained strategic alignment that defines US efforts in areas like frontier artificial intelligence (AI).

For brownfield strategies that repurpose existing facilities, geographic advantage accrues to regions with existing chemical infrastructure that can be repurposed. European and US chemical complexes offer potential brownfield sites, but capturing that advantage requires partnerships with incumbent chemical platform operators and feedstock supply chains that can deliver both low cost and reliability.

[16] Marlowe, Matt. China's Biomanufacturing Play: The Quiet Industrial Revolution No One Is Watching. Biocross. Nov 20, 2025. https://www.bridgecross.bio/chinas-biomanufacturing-play-the-quiet-industrial-revolution-no-one-is-watching/
[17] The Net-Zero Industry Act. European Commission. May 2024. https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en
[18] Strategic Framework for a Competitive and Sustainable EU Bioeconomy. November 2025. https://environment.ec.europa.eu/publications/bioeconomy-strategy_en

Platform Learning Effects

A final strategic consideration: Early deployment in one molecule creates learning and cost reductions that transfer across the platform.

The lysine precedent is instructive. The journey from pharmaceutical specialty to mass-market commodity took 30 years, with prices dropping from $80–90 per kilogram to less than $1 per kilogram, reaching 3.6 million metric tons today. The drivers: strain engineering, fermentation optimization, and downstream processing improvements. Those drivers accumulated as transferable capabilities. Expertise developed for one molecule accelerates the next.

Mature chemical processes have largely exhausted their cost reduction potential. In contrast, biotechnology offers the potential for sustained cost deflation as strains improve, processes are optimized, downstream operations mature, and capabilities are shared.

The following sections identify potential learnings, platform linkages, and the sequencing logic that enables early wins to unlock subsequent opportunities.

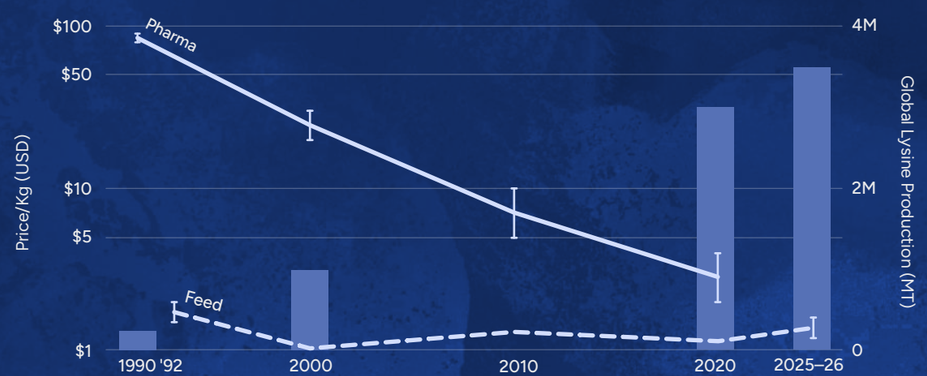
The Lysine Precedent: A Blueprint for Bio-Based Cost Reduction

Lysine's 30-year journey: from tens of dollars per kilo in early pharma use to a multi-million-ton bulk commodity produced at close to 1 USD/kg.

Lysine started as a pharma-like ingredient: tens of dollars per kg in small, clinical volumes."

Fermentation enables feed-grade entry; prices drop to low single-digit USD/kg as volumes cross hundreds of thousands of tons.

Today: ~3–3.5M MT/year, feed-grade at roughly 1–1.5 USD/kg, pharma/food-grade only a modest premium—the pharma price track becomes economically irrelevant at scale."



Microbial fermentation started to displace synthetic lysine in the 1960s–1970s and, by the 1980s, had become the dominant production route; since at least the early 1990s, virtually all industrial L-lysine has been produced by fermentation, enabling the scale-up from tens of thousands to millions of tons per year.

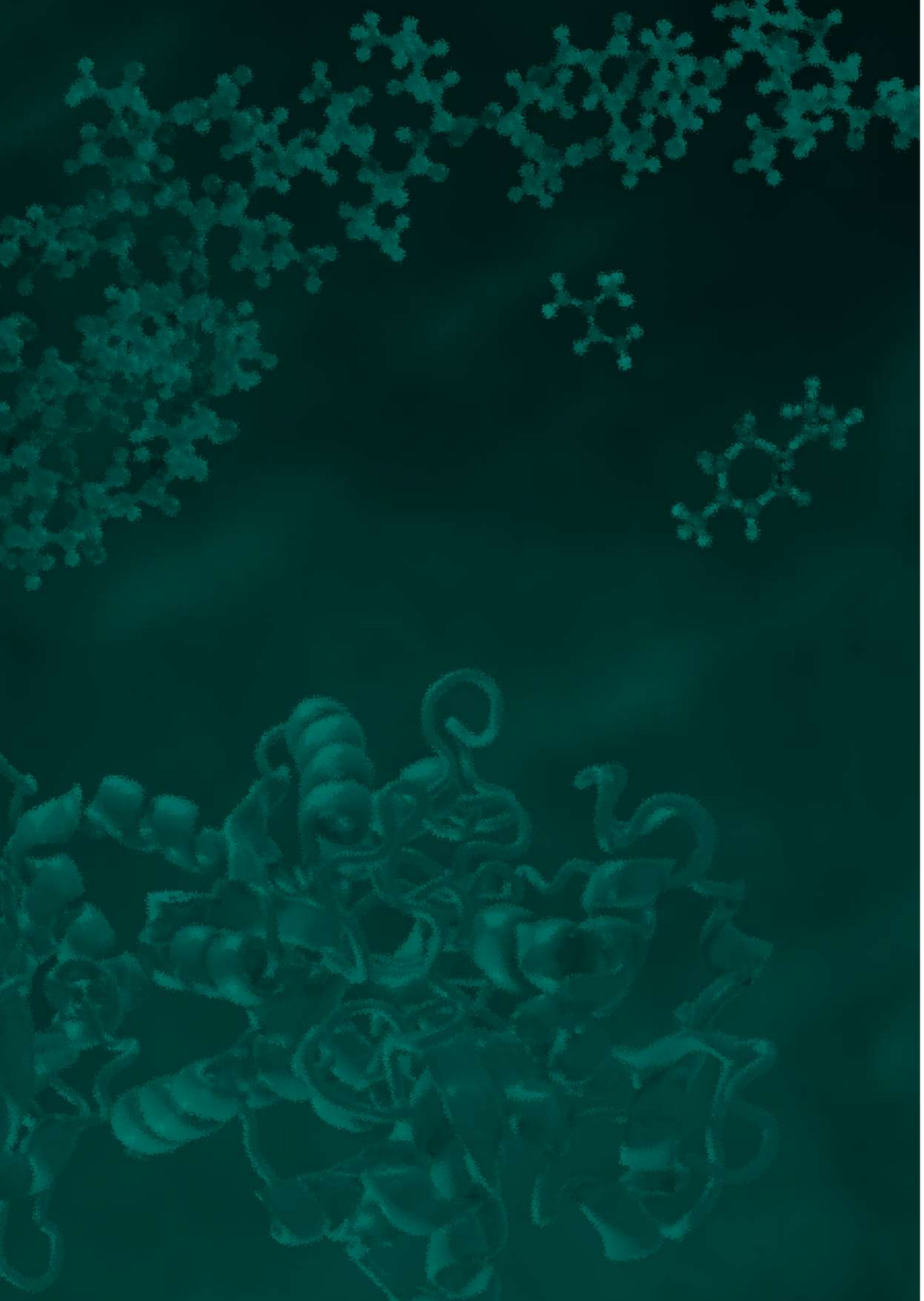
1990–2010 values are interpolated from FAO and biotech reviews; 2015–2024 anchored on published global production estimates.

3: MOLECULES AT A GLANCE

The four priority molecule families that follow were selected through a prioritization process combining quantitative screening, expert interviews, and workshop validation. Each molecule family meets selection criteria for market size, biotech addressable opportunity, and either performance differentiation or drop-in compatibility that justifies adoption.

The table provides a side-by-side comparison across key dimensions. Detailed analysis for each molecule family follows in Section 4.

	TERPENES	PEPTIDES	NON-CATALYTIC PROTEINS	HYDROXY ACIDS
Market size (2030)	$7–12B	$2.2–3.4B	$21–31B	$1.8–2B (excl. citric/lactic)
Biotech potential (2030)	>$1B across specialty + platform molecules	>$1B across food, cosmetics, ag	>$1B in functional proteins	>$1B (3-HP/acrylic acid pathway alone)
Unit price range	$1–10/kg (isoprene, menthol) to $100s–1000s/ kg (nootkatone, carotenoids)	$50–400+/kg	$10–400+/kg	$2–15/kg
Key applications	Flavors and fragrances, cosmetics (squalane), rubber (isoprene), agriculture	Food preservation, cosmetics (e.g., anti-aging), biopesticides, medical nutrition	Infant/sports nutrition, dairy analogs, cosmetics (collagen, silk), textiles (silk)	Polymers (PLA, acrylates), SAPs/ diapers, food acidulants, solvents
Business-as-Usual pain points	Harvest volatility, petrochemical feedstock swings, limited access to rare analogs	Chemical synthesis expensive at scale, supply variability, narrow activity profiles	Avian/swine flu disruptions, allergens, animal welfare, GHG/ water/land footprint	Hazardous reagents, energy-intensive synthesis, feedstock price volatility
Near-term milestones (0–5 yr)	Specialty flavors and fragrances scaling (patchoulol, squalane already commercial); platform reliability demonstration across family	Discovery platforms operational; cosmetics PFAS alternatives; Vestaron ag scaling	β-lactoglobulin commercial (Perfect Day); casein mozzarella (New Culture); sweet protein pilots	3-HP demo plants; offtake agreements with leading absorbent products manufacturers; strain optimization to ~90% yield
Long-term potential (5–10 yr)	Isoprene at $5,000/ton; $100M non-isoprene revenue; natural rubber replacement	Platform to produce any peptide at kg scale; >$100M across molecules	Platform ecosystem; functional proteins across food/cosmetics/ materials	$1B bio-acid revenue; 100 kt scale; next-gen feedstocks
Infrastructure requirements	New multipurpose fermentation; deliberate product family clustering	New dedicated capacity; multi-use modular plants	New dedicated capacity; improved filtration/drying	Brownfield integration; existing chemical infrastructure
Key regulatory drivers	"Natural-identical" labeling in flavor & fragrances; US Environmental Protection Agency (EPA) registration (nootkatone)	US GRAS established; EU Novel Foods slow; PFAS phase-out; EPA biopesticide registration for ag	US GRAS faster; EU Novel Foods not yet authorized; labeling restrictions	Drop-in compatibility simplifies approval; sustainability claims for consumer products; process safety (eliminates hazardous reagents)
Coalition acceleration opportunities	Demand aggregation; IP pre-licensing); JDA pilot facilities	Shared discovery library; in silico + HTS platforms; IP licensing coordination	Define priority proteins; "we buy if..." commitments; shared pilot/testing facilities	Demand aggregation across CPG buyers; brownfield site identification; feedstock supply coordination



4: PRIORITY MOLECULE GROUPS

Introduction

Four molecule families emerged from a prioritization process combining quantitative screening, thirty expert interviews, and validation at a November 2025 industry workshop. Each molecule family meets the selection criteria that guided this analysis:

- sufficient market size to justify scale-up investment,
- realistic addressable opportunity for bio-based routes,
- performance advantages or drop-in compatibility that justify adoption, and
- a credible path to cost competitiveness against incumbent production methods.

These four—families, terpenes, peptides, non-catalytic proteins, and hydroxy acids—do not represent a single deployment logic. They divide into two distinct tracks, and understanding this distinction is essential for matching investment thesis, infrastructure strategy, and go-to-market approach to each opportunity.

Two Tracks to Scale

Track 1: Performance molecules competing on function

Peptides, non-catalytic proteins, and specialty terpenes represent a different value proposition. **These are low-volume, high-value molecules**

where biology's advantage lies not in cost reduction but in functional performance that incumbents cannot deliver: novel bioactivities, improved stability, superior purity, or properties that enable new formulations.

The challenge here is market adoption. New performance must find its use case, be validated in product development pipelines, and be valorized at appropriate price points. History shows this can take considerable time: the path from demonstrated function to commercial traction requires realistic timelines and deliberate de-risking.

against strain engineering cost and timeline

- Capital expenditure requirements for commercial-scale facilities, whether retrofitted or new-build
- Feedstock costs and their volatility
- Sufficient demand aggregation to justify FOAK plant investments

These molecules are candidates for brownfield deployment (bolt-on integration with existing chemical infrastructure) rather than purpose-built biomanufacturing facilities.

> The challenge is not proving that fermentation works. The challenge is proving that fermentation economics work at scale.

These molecules require new multipurpose fermentation and downstream processing infrastructure. Success depends on early demonstration of market-valued performance, co-development partnerships with downstream users, and capital structures that reflect the hybrid risk profile between venture and infrastructure while accommodating longer commercialization cycles.

The governing question for Track 1: *How do we accelerate the path from novel function to validated market demand?*

Track 2: Platform molecules competing on cost

Hydroxy acids and small-molecule terpenes (isoprene, monoterpenes) are high-volume opportunities where biology must achieve cost parity with petrochemical or extractive incumbents.

The challenge is not proving that fermentation works. The challenge is proving that fermentation economics work at scale.

Success in this track depends on explicit techno-economic parameters:

- Yield, titer, and productivity targets that balance technical achievability

The governing question for Track 2: What specific technical and economic conditions must be met to displace established petrochemical routes?

The Question Each Molecule Must Answer

For each molecule family, this report answers a fundamental question:

Why is biology a unique route to this molecule, and what does it offer that incumbents cannot?

The answers vary. In some cases, biology enables access to molecules that are difficult or impossible to synthesize chemically. In others, fermentation offers stereochemical precision, reduced process hazards, increased sustainability, or independence from volatile petrochemical feedstocks.

For functional molecules, biology provides design freedom: the ability to engineer properties that exceed what nature or chemistry alone can deliver.

These advantages must be grounded in demand-side validation, not supply-side optimism.

What Each Section Covers

The four molecule chapters follow a consistent structure:

- **Commercial case:** Market size, growth trajectory, key applications, incumbent production routes and their pain points, and the specific wedge where biology offers an advantage
- **Technical and infrastructure reality:** Technology readiness, production economics, downstream processing complexity, and whether the molecule suits brownfield (retrofitting existing chemical infrastructure) or requires new-build facilities (purpose-designed fermentation and DSP capacity)
- **What it takes to succeed:** Critical assessment of the parameters, investments, and timelines required, including risks and uncertainties, particularly regulatory timelines
- **Near-term proof points**: The most promising early demonstrations and what coordinated industry action could accelerate

A Note on Cost Drivers

DSP is frequently cited as the universal bottleneck in biomanufacturing. This is accurate for high-value, low-volume molecules where purification complexity dominates production costs. But for commodity-scale molecules like hydroxy acids, feedstock costs and bioconversion efficiency matter equally or more. This report avoids sweeping generalizations: cost drivers are assessed by molecule.

The sections that follow examine each priority molecule family in turn: terpenes, peptides, non-catalytic proteins, and hydroxy acids.

The 4 Molecule Classes in Summary

Terpenes:

Near Market-ready

Applications: Flavors, fragrances, rubber.

Peptides:

High-value, high-performance

Applications: Food preservation, cosmetics, biopesticides.

Non-Catalytic Proteins:

Functional future

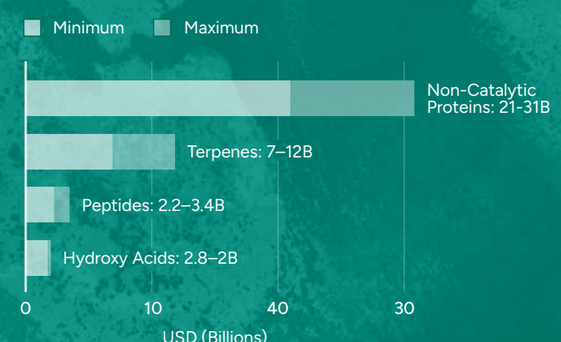
Applications: Infant/sports nutrition, cosmetics, dairy analogs.

Hydroxy Acids:

Long-term platform play

Applications: Polymers, diapers, solvents.

2030 Market Estimates by Molecule Family



4.1 TERPENES

The Market-Ready Quick Win

Commercial Case

Terpenes and terpenoids occupy a distinct position among the four priority molecule families: the market-ready opportunity. Established buyers exist, bio-based production is already commercial for several molecules, and platform economics allow a single fermentation infrastructure to serve multiple products.

The global market spans $7–12 billion annually and is growing at 3–4% per year, with unit prices ranging from $1–10 per kilogram for commodity molecules like isoprene and menthol, to hundreds or thousands of dollars per kilogram for specialty compounds like nootkatone, astaxanthin, and zeaxanthin.

The applications are remarkably diverse.

- In personal care, terpenes provide emollients (squalane), fragrances (limonene, patchoulol, geraniol), and cooling agents (menthol/mint).
- In food and beverage, they deliver flavor and fragrance actives such as nootkatone and linalool.
- Agriculture uses include EPA-registered insect repellents and antimicrobial agents.

Perhaps most significantly for volume, terpenes serve as synthetic rubber monomers (isoprene) and lubricant base oils. Farnesene has found commercial applications spanning animal nutrition, cosmetics, flavors and fragrances, and as a jet fuel blendstock.

The customer base includes global flavor and fragrance houses, major cosmetics brands, and tire and adhesives manufacturers.

Today's production routes face significant constraints.

The challenge with terpenes is not proving that biology works—it is sequencing investment across a large and diverse molecule family to maximize early wins while building toward higher-volume opportunities.

- Isoprene serves a captive rubber market where demand is guaranteed as long as costs can be met. Petrochemical production depends on volatile C5 cracker economics, creating an opening for cost-competitive bio-based alternatives.
- Botanical extraction is inherently volatile: citrus harvests fail, patchouli leaf availability fluctuates, and geopolitical risks threaten sourcing.
- Natural rubber markets face persistent supply-demand imbalances, compounded by concerns over deforestation.

For downstream users, the pain points are clear: price spikes, harvest failures, inconsistent olfactory profiles, and limited access to rare analogs. Some terpenoids are difficult or impossible to extract from plants on a commercial scale.

Biology offers a compelling wedge into these markets.

Fermentation decouples supply from harvest volatility and feedstock swings, though sugar feedstock costs and availability introduce their own variability that must be managed.

The performance case is equally strong.

Biological production delivers built-in stereocontrol, producing the correct isomer rather than racemic mixtures, with DSP then required to reach final purity specifications.

Labeling advantages matter in consumer-facing markets.

"Natural-identical" claims in perfumery and animal-free positioning (“shark-free squalane”) can command premium pricing. Most importantly, biology enables access to rare terpenoid analogs, such as nootkatone from valencene (a fragrant sesquiterpene found in citrus), that remain inaccessible through extraction or traditional chemistry. The economic case has already been proven in specific applications.

For commodity terpenes, biotech costs have reached approximately $1.50 per kilogram, approaching parity with conventional routes[19] [20]. For high-value extracts, parity has arrived, differentials of 0 to 20% are now typical.

More than a decade ago, Amyris demonstrated titers exceeding 100 grams per liter for farnesene[21, 22]. Shark-free squalane from sugarcane fermentation sells at $30–50 per kilogram, making it competitive with plant and synthetic routes[23].

[19] McCoy M. Amyris puts a price on farnesene. C&EN. 19 October 2019. https://cen.acs.org/articles/93/i41/Amyris-Puts-Price-Farnesene.html
[20] Ferreira R. et al. Production of farnesene (a terpene) via fermentation process modeling and techno economic assessment (TEA) using superpro design. May 2020. https://www.researchgate.net/publication/341103805_Production_of_Farnesene_a_Terpene_via_Fermentation_-_Process_Modeling_and_Techno-Economic_Assessment_TEA_using_SuperPro_Designer?channel=doi&linkId=5ead915fa6fdcc7050a2beff&showFulltext=true
[21] Hill P. et al. Clean manufacturing powered by biology: how Amyris has deployed technology and aims to do it better. J Ind Microbiol Biotechnol. 2020 Oct. https://pmc.ncbi.nlm.nih.gov/articles/PMC7695652/
[22] Meadows AL et al. Rewriting yeast central carbon metabolism for industrial isoprenoid production. Nature. 2016 Sep 29;537(7622):694-697. doi: 10.1038/nature19769. https://www.nature.com/articles/nature19769
[23] Recent supplier quotations place cosmetic-grade squalane broadly between about $20 and 80/kg, with many offers in the $30–50/kg range. Source: Accio.com https://www.accio.com/plp/squalene-price-per-kg

Technical and Infrastructure Reality

Technology readiness varies significantly across the terpene family.

- Artemisinin, astaxanthin, bisabolol, CoQ10, farnesene, hemisqualane, manool, nootkatone, patchoulol, santolols, sclareol, squalane, squalene, and valencene have reached commercial production.
- Bio-isoprene, citronellal, and linalool are advancing through pilot scale.
- Alpha-ionene, bisabolene, and limonene are still in early development.

With more than 300 known terpenes, the opportunity space is large—but no single company can pursue them all. The strategic value of terpenes lies in their platform logic.

> The economic case has already been proven in specific applications.

A single fermentation host and process can produce multiple monoterpenes priced below $10 per kilogram. Oily terpene products share similar downstream processing requirements, enabling what experts describe as an "oily product platform" where learnings transfer across molecules.

The underlying biochemistry explains why: the core metabolic pathways (MEP, or methylerythritol phosphate, and MVA, or mevalonate) serve as precursors for sterols, terpenoids, and carotenoids, with structural families building sequentially from C5 (isoprene) to C10 (monoterpenes), C15 (sesquiterpenes), and C20 (diterpenes).

This platform logic supports two distinct scaling tracks.

1. High-value specialty—terpenes, patchoulol, nootkatone, squalane—offer lower volumes but higher margins and faster qualification cycles. These represent near-term commercial opportunities.
2. Platform terpenes like isoprene and farnesene target high volumes at lower margins, competing directly with petrochemicals. Isoprene sits in a captive rubber market where demand is effectively guaranteed if bio-based production costs become competitive with petrochemical routes.

The coalition estimated that C5 and C10 molecules will be difficult to achieve at scale within five years, but an isoprene plant is plausible on a ten-year horizon.

Downstream processing presents a primary technical challenge, and the difficulty varies by chain length.

C5 molecules, such as isoprene, require capturing a low-boiling gas from fermentation broth, an energy-intensive process with complex phase behavior[24]. C10 monoterpenes create host toxicity problems, requiring in-situ product removal to strip them during fermentation[25]. Larger terpenes (C15 and above) present easier DSP but address smaller individual markets. Across the family, downstream processing, particularly solvent selection, distillation, and biphasic fermentation, adds complexity and cost[26].

Additional technical risks associated with terpenes include:

- Ongoing strain optimization challenges
- Chemical CapEx and safety risks from secondary reactions for terpene upgrading (e.g., converting farnesene to squalane)
- Labeling debates over "biotech–natural" versus "naturally extracted" designations, which affect pricing tiers in fragrance and flavor markets

Infrastructure requirements present a mixed picture. For specialty terpenes, the entry path is incremental: purpose-built purification capacity added to existing fermentation facilities can support early commercial volumes without greenfield investment. Scaling to platform volumes across the broader terpene family will require dedicated multipurpose fermentation facilities. The broad compound class requires different downstream processing for each molecule, though deliberate clustering of product families with similar DSP requirements can improve facility utilization.

[24] Ye L. et al. Engineering microbes for isoprene production. Metabolic Engineering. November 2016. 38:125-138. https://doi.org/10.1016/j.ymben.2016.07.005
[25] Brennan T. et al. Alleviating monoterpene toxicity using a two-phase extractive fermentation for the bioproduction of jet fuel mixtures in Saccharomyces cerevisiae. Biotechnol Bioeng. DOI: 10.1002/bit.24536.
[26] Tuo L et al. Molecules. Two-phase fermentation systems for microbial production of plant-derived terpenes.2 March 2024. doi: 10.3390/molecules29051127

What It Takes to Succeed

Near-term success over the next five years depends on focusing on high-value specialty terpenes with fast qualification cycles. Patchoulol, squalane, and nootkatone represent the clearest opportunities.

Building confidence for larger platform investments (C5 → C10 → C15) requires demonstrating reliability at each step, starting with pilot investments that prove the concept at a meaningful scale. Securing customer commitments from flavor and fragrance buyers to target cost levels can further de-risk scale-up and unlock larger investment.

Long-term success over five to ten years requires achieving isoprene production at a commercial scale with costs competitive with those of petrochemical routes. This demands optimized strains, low-cost fermentation approaches, and DSP and chemistry optimization working in concert. The collective target: $100 million in non-isoprene terpenes revenue and at least one commercial plant running within ten years. The natural rubber replacement pathway remains a significant prize if technical and economic hurdles can be cleared.

Critical techno-economic parameters for small-molecule terpenes (yield and titer targets sufficient to close the economics, CapEx requirements for multipurpose facilities, and feedstock cost sensitivity) require additional analysis. Contract manufacturing organizations (CMOs) can mitigate early-stage risk before major CapEx commitments. Still, this work represents a gap that must be filled before investment decisions on commodity-scale terpenes can be made with confidence.

> Near-term success over the next five years depends on focusing on high-value specialty terpenes with fast qualification cycles. Patchoulol, squalane, and nootkatone represent the clearest opportunities.

Recommendations

Terpenes represent the "quick win" category for industrial biotechnology: existing market pull, clear cost targets, and proven demand. Success here creates credibility and momentum for the broader platform, unlocking C15s, C20s, and carotenoids.

Coordinated industry action can accelerate progress through several mechanisms.

- Demand aggregation can fund scale-up investments that no single customer would underwrite alone when offtake commitments are pooled from multiple buyers.
- Value chain marketing that positions bio-terpenes to enhance supply resilience and differentiate performance can accelerate adoption.
- Clarity on intellectual property, including pre-licensing strain and DSP IP from incumbents, removes a significant barrier.
- Joint development agreements for pilot facilities can share risk across participants.
- AI-driven pathway optimization and high-throughput screening can accelerate structured discovery mapping across molecule families to efficiently identify the most promising use cases and guide sequence development.

The most promising early proof points include specialty flavor and fragrance molecules (patchoulol, valencene) and cosmetic terpenes (squalane, bisabolol) that have already reached commercial production, carotenoids addressing a $1 billion market with scale benefits, and isoprene as a high-volume anchor molecule if cost hurdles can be cleared.

Market Realities

Established incumbents in the chemical and flavor and fragrance sectors drive the market rather than startups, which shapes partnership dynamics. Small individual markets for specific terpenes make development cost versus return-on-investment calculations challenging, reinforcing the importance of platform approaches that amortize strain and process development across multiple products. Chinese producers already dominate several bulk terpene streams, such as pine-derived products, and China's terpene market is growing at high single-digit CAGRs, intensifying global competition in commodity terpenes.[27]

[27] China Terpenes Market Share 2025-by Region | by Application | by Type. Luminary Vision Co. October 2025. https://www.linkedin.com/pulse/china-terpenes-market-share-2025-by-region-application-dotje/.

4.2 PEPTIDES

The Long-Game Platform

Commercial Case

Peptides occupy a distinct position among the four priority molecule families: a market size smaller than proteins or hydroxy acids, but with premium pricing, high potency at low doses, and application breadth that includes food, personal care, agriculture, and advanced materials.

The non-therapeutic peptide market (synthesis, cosmetics, food, and research applications) is valued at approximately $3–6 billion today and is projected to grow to $8–12 billion by the early 2030s at 7–9% annually[28]. Bulk unit prices for established antimicrobial peptides such as nisin start at $50–100/kg, while specialty peptides such as pediocin exceed $400/kg due to their more complex production[29].

End markets reflect this diversity.

- Food and beverage applications include natural preservatives, texture and shelf-life enhancement, medical nutrition, sports and active nutrition, and gut and immune support.
- Personal care products use peptides as antioxidants, skin-conditioning agents, preservative boosters, and anti-aging actives commanding premium pricing in cosmeceutical formulations.
- Agriculture represents a growing opportunity for biopesticides with novel modes of action.

[28] Peptide Synthesis Market Overview 2026 Forecast Through 2030. Market Pulse Point. January 7, 2026. https://marketpulsepoint.wordpress.com/2026/01/07/peptide-synthesis-market-overview-2026-and-forecast-till-2035/
[29] Global Nisin price. Tridge. 2025. https://dir.tridge.com/prices/nisin

- Advanced materials and bioprocessing applications include antimicrobial coatings and fermentation process control.

Potential customers span food and beverage players ($8–9T global revenue), beauty and personal care companies ($0.6T), and crop protection leaders ($80–85B).

Within these markets, the molecule family divides into functional categories.

- Food preservatives include nisin, which provides anti-Listeria activity in cheese and meats, and pediocin, a broader antimicrobial.
- Nutrition peptides include glutathione, valued as an antioxidant, redox buffer, and flavor modifier, and glycomacropeptide (GMP), a phenylalanine-free peptide for PKU nutrition with prebiotic activity and mineral binding properties.
- Cosmetic peptides include elastin-like polypeptides (ELPs) for skin care and nutraceutical applications, as well as signal peptides that stimulate collagen production.
- Agricultural peptides include spider venom derivatives, defensins, and cyclotides that function as targeted insecticides with novel modes of action. Emerging approaches also use micropeptides to regulate gene expression in crops.

Conventional production routes face mounting structural limitations. Chemical synthesis remains expensive at scale and is often technically unfeasible for larger, more complex molecules such as peptides exceeding 40–50 amino acids. Similarly, extraction from natural sources introduces significant supply variability and impurity challenges.

Biotechnology provides a decisive unlock here: It offers the only viable pathway to produce these high-performance long-chain molecules with the purity and consistency required for industrial adoption.

Many building blocks are already commoditized, making the core strategic question "which peptides to choose" rather than "how to make peptides." Incumbent chemical preservatives (broad-spectrum and low-cost) have high customer acceptance creating a risk for food producers considering novel molecules with narrower activity profiles.

The biological case for peptides rests on their quality, specificity, and potential for customization. Fermentation delivers consistent purity that extraction cannot match, while their inherent specificity and low immunogenicity make them high-performance actives across applications.

Innovation potential is substantial: variants such as Nisin Q and Nisin Z demonstrate how targeted modifications can improve stability and solubility, while chirality control allows producers to isolate the single active form that matters metabolically. In cosmetics, bioactivity advantages, including superior skin penetration and collagen stimulation, are already well established.

Market momentum is building from multiple directions. Regulatory restrictions on PFAS are accelerating reformulation, and biologically produced peptides offer three main benefits: production processes free of PFAS-related concerns, a path to lower manufacturing costs for existing peptides, and access to novel peptides with new and/or additional biological properties.

Simultaneously, the rise of GLP-1 medications—a class of therapeutic peptides used for diabetes and weight management—has driven interest and raised broader awareness and acceptance of peptide-based products across categories. By demonstrating that peptides can be manufactured safely and effectively at a significant scale, the GLP-1 success story has cleared a path for peptide-based products in cosmetics and nutrition, effectively bridging the gap between pharmaceutical excellence and consumer-facing bio-based ingredients.

Biotechnology provides a decisive unlock here: It offers the only viable pathway to produce these high-performance long-chain molecules with the purity and consistency required for industrial adoption.

Current economics favor specialty applications. Specialty peptides command premium pricing at low doses, and the value currently sits primarily in discovery rather than manufacturing scale.

The performance–price ladder:

- Pharma (60–80% gross margins)
- Ag peptides, specialty biopesticides, and targeted ag actives (40–60% gross margins)
- Specialty and personal care (30–50% gross margins)
- Food (20–30% gross margins)
- Feed and commodity (5–15% gross margins)

Scaling requires significant capital—more than $20 million for production facilities with long timelines of 7 to 8 years or more, and downstream processing significantly driving the final price.

Technical and Infrastructure Reality

Technology readiness varies across the peptide family.

- Nisin, glutathione, and cosmetic peptides are now in commercial production.
- Pediocin and spider-venom peptides sit at demonstration scale.
- Flavor peptides and elastin-like polypeptides remain at the pilot stage.

The active player landscape includes established ingredient companies (IFF with Nisaplin, DSM-Firmenich with DelvoNis, Croda, Clariant, Gelita AG, and Lonza) alongside agricultural specialists (Invaio, Syngenta, and Vestaron, whose SPEAR® biopesticide products are scaling field deployments).

Production challenges are significant but nuanced.

While individual peptides often have a primary mode of action, many offer multifunctionality. For example, a cosmetic peptide that stimulates collagen production might also provide antimicrobial protection, or a food texture enhancer could deliver antioxidant benefits. This multifunctionality creates opportunities to justify premium pricing through stacked value propositions. That said, complex downstream processing is often required, lowering overall production efficiency.

Formulation development is essential to increase stability against biological, thermal, and chemical degradation: peptides are inherently sensitive to heat, pH, and proteases, and frequently require carriers, encapsulation, or preservatives. Achieving economically attractive titers and yields for peptides remains difficult. Most reported systems reach only mg/L to low single-digit g/L titers, and longer, more complex peptides are particularly challenging to push beyond this range. As of this writing, no single obvious chassis organism has emerged for peptide production.

Technical advantages provide countervailing opportunities.

Chassis strains and platforms analogous to those that transformed enzyme manufacturing could emerge for peptides. Screening can be conducted at tiny volumes, and the discovery phase can leverage chemical synthesis routes at the milligram scale before committing to biological production. AI-driven approaches and high-throughput screening are accelerating molecule prioritization, reducing the wet-lab iteration cycles that historically extended development timelines.

Infrastructure requirements place peptides alongside terpenes and proteins: purpose-built facilities are likely needed at scale rather than brownfield integration with chemical infrastructure. In the near term, however, existing precision fermentation capacity (contract manufacturers, enzyme plants) may be adaptable for early low-volume production, providing a bridge before dedicated facilities are justified. Longer-term, purpose-built facilities designed for modern fermentation technology will likely outperform compromise brownfield conversions, both in process flexibility and capital efficiency.

The economics improve through multi-use design. Heavy capital expenditure is front-loaded, but multi-use facilities and modular plants can serve multiple peptide products across industries once built. Multiproduct, multi-segment plants increase capital effectiveness and enable dynamic switching between markets—personal care versus feed, for instance—as economic conditions

shift. Downstream synergies across peptide products can improve economics and simplify processing.

Unlike mature commodity chemicals, where pricing is largely dictated by volatile feedstock and energy costs, biotechnology is in a high-growth optimization phase, particularly in the peptide space.

The lysine precedent offers a critical reference point for engaging chemical companies. The journey from pharmaceutical specialty to mass-market commodity took thirty years, from $80–90 per kilogram three decades ago to 3.6 million metric tons produced today at less than $1 per kilogram. This transformation required extensive process improvement over time, demonstrating that sustained investment combined with iterative optimization leads to eventual mass-market success.

Because the bio-based peptide production processes are not yet commoditized, they offer a unique window for sustained cost reduction through improvements in strain yield, fermentation titers, and downstream processing. This "optimization runway" is a critical narrative for investors: It transforms peptides from high-cost specialties into scalable industrial assets with a predictable path to margin expansion.

Regulatory Landscape

Regulatory pathways follow familiar geographic patterns. In the US, the GRAS pathway is well-established for certain food peptides, with nisin and other bacteriocins having successfully navigated the approval process. The EU Novel Foods pathway moves more slowly. Novel peptides fall under the Novel Food framework, with uncertain timelines for authorization.

Positioning considerations differ by market. US and EU consumers respond to different regulatory and perception frameworks. Bio-based peptides combine hard technical performance claims with consistent purity and supply reliability that conventional routes struggle to match.

What It Takes to Succeed

For peptides, near-term priorities should center on discovery and demand validation. The core question is which peptides to pursue. Answering that requires parallelized prototyping, high-throughput screening, and in silico and AI-based approaches to efficiently narrow the field.

Once candidates emerge, a platform and toolbox model makes sense, with segmentation by outlet: high-margin human applications at the top, mid-range specialties in the middle, and lower-margin feed at the bottom. Regardless of where a peptide sits on this ladder, business models must be "buy-in" from the start: co-development with committed strategic customers rather than build-it-and-they-will-come. Specific end users with demonstrated need should be identified before major capital commitments are made.

Application priorities reflect where pull is strongest.

- Regulatory restrictions on PFAS are driving innovation in peptide production processes. Anti-aging and skin repair applications command premium pricing.
- In agriculture, cost sensitivity is paramount: the $5 per hectare (approximately 2.5 acres) for pesticides sets the economic bar. Vestaron's SPEAR® products demonstrate that bio-based approaches can compete.
- In food preservation, label-friendly antimicrobials address clean-label trends that show no sign of abating.

The longer-term vision centers on platform capability. The goal is to develop the ability to produce any peptide at commercial scale—kilograms for specialty applications and tons for agriculture and food preservation—supported by chassis strains that enable faster development and multi-product facilities.

Roll-out logic dictates starting in higher-value, lower-volume segments and cascading down the price ladder as costs reduce through process improvement and scale.

The collective target: more than $100 million across peptide molecules. Near-term priorities include high-value cosmetics peptides and systems for sample production to support discovery and application development. Agricultural and food applications are medium-term.

Recommendations

Peptides share strategic questions with non-catalytic proteins—questions no single company can resolve alone.

- *Who should focus on discovery?*
- *Should a dedicated organization be created specifically for peptide innovation?*
- *Is discovery pushed to customers or pulled by a central coordinating entity?*

The answers will shape how quickly the industry moves from fragmented experimentation to coordinated scale.

Coalescing demand to fund offtakes is essential: securing commitments from major consumer goods companies to purchase volumes would de-risk capital investment. Coordination of IP licensing could accelerate development by reducing friction around freedom to operate concerns.

Picking an approach and recruiting the right partners matter more than pursuing every opportunity simultaneously. Setting industry roadmaps for target sectors—personal care, agriculture, or food—would align efforts and signal direction to potential investors.

Practical infrastructure for discovery would accelerate progress:

- A shared library of peptides to help the industry identify targets faster than individual company efforts, particularly in agriculture, food, and materials applications, where pre-competative collaboration is more feasible
- In silico modeling combined with high-throughput synthesis and screening for molecule definition, performance characterization, expression in reactors, and application prioritization
- Shared facilities to keep costs down during capital-intensive early stages
- A pre-fab supply chain approach using contract development organizations rather than owned plants initially
- Multi-product pilot plants designed from the start for peptide DSP, serving multiple players and applications
- Assay platforms paired with high-throughput screening to systematize the discovery-to-application pipeline

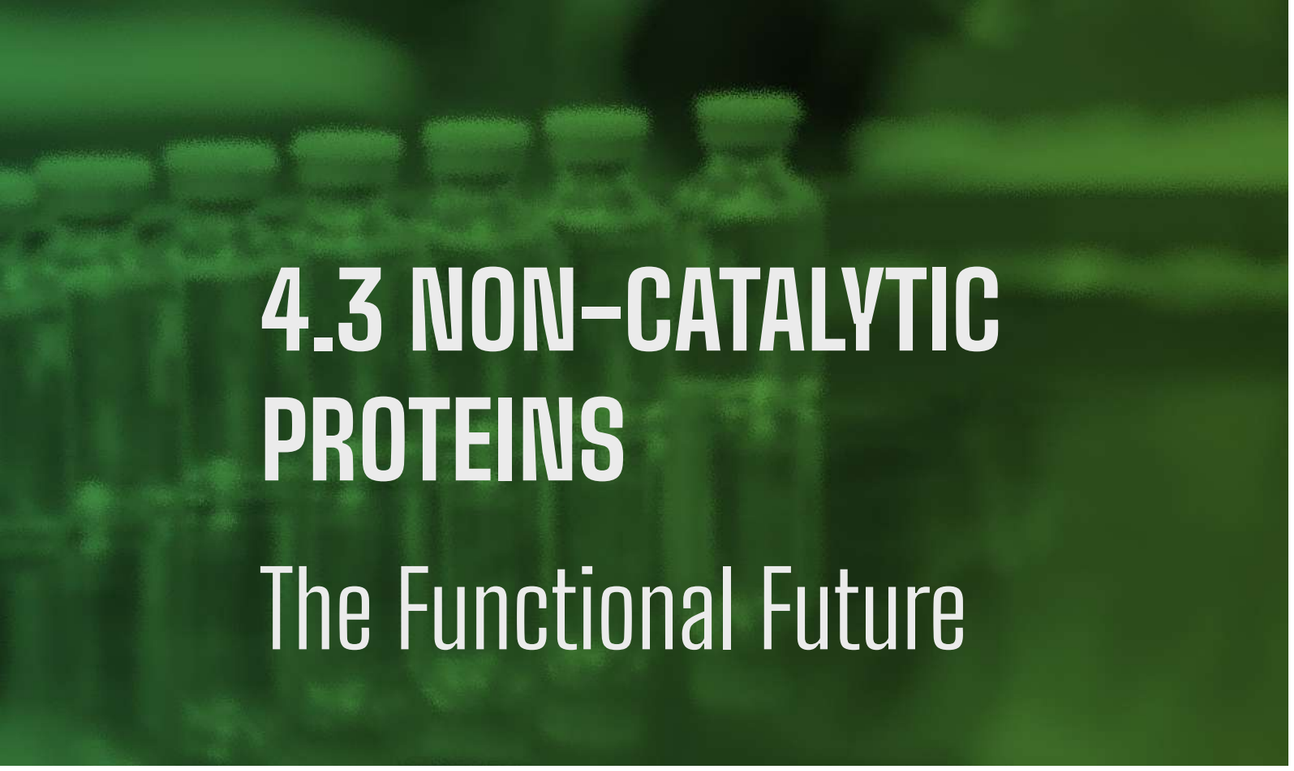
Market Realities

Peptides face several structural challenges:

- Lower-volume stock-keeping units (SKUs) with fragmented demand make them harder to scale than molecules with concentrated buyers
- Stability and formulation challenges that add development time and cost
- Building blocks are already commoditized in many cases: the strategic question is which peptides to prioritize, not whether peptide chemistry works
- Limited access to dedicated plants and CMOs
- No clear chassis strategy across the industry

Reframing the narrative is part of the work. The future story should emphasize multi-industry applicability and the advantages of modular, multi-use facilities. It should anchor investment decisions in validated end-user needs and point to the lysine precedent as proof that bio-based production costs decrease meaningfully at scale.

The peptide opportunity is real, but capturing it requires patience, coordination, and disciplined focus on applications where biology's advantages translate into commercial returns.



4.3 NON-CATALYTIC PROTEINS

The Functional Future

Commercial Case

Non-catalytic proteins represent the largest addressable market among the four priority molecule families and the longest commercial horizon. Precision fermentation has proven it can produce functional proteins at competitive cost in select applications. The challenge is identifying where differentiated performance justifies the investment required, and building the demand signals, shared infrastructure, and regulatory pathways that turn demonstrated functionality into commercial scale.

The total market for non-catalytic proteins, including conventionally produced dairy, egg, and structural proteins, is approximately $21 billion today, growing to over $31 billion by 2030 (nearly 8% annually). Demand spans 1.4 to 2.0 million metric tons. Precision fermentation targets a share of this market by offering functional and supply chain advantages over conventional extraction[30].

Unit prices vary dramatically depending on function and purity, from $10 per kilogram for commodity proteins (casein, ovalbumin, lactalbumin) to $400 or more per kilogram for specialty molecules like elastin and sweetener proteins (brazzein and thaumatin).

End markets cut across sectors.

- Food and nutrition applications dominate in infant formula, sports nutrition, protein-enriched foods, dairy products including cheese and milk analogs, bakery, and confectionery.
- Personal care uses film-forming and conditioning proteins in hair and skin products, with collagen playing a significant role in cosmetics.
- Textiles represent an emerging opportunity through silk proteins (fibroin and spidroin) that offer high tensile strength and controlled biodegradability.
- Niche applications include casein in paper and wood adhesives and silk proteins in food films and coatings.

Potential customers include infant formula manufacturers, sports nutrition companies, consumer goods companies, and foodservice innovators.

The molecule family encompasses several distinct protein classes:

- **Dairy proteins** include casein, the primary milk micelle protein; beta-lactoglobulin, valued for its functional properties and role as a vitamin carrier; and alpha-lactalbumin, essential for infant and sports nutrition applications.
- **Egg proteins** center on ovalbumin, which delivers excellent foaming, emulsification, and heat-set gelation, along with vitellogenin as the egg yolk precursor protein.
- **Structural proteins** include collagen, which provides tensile strength and gelling properties; elastin, used for film-forming and moisturizing applications; and silks prized for high tensile strength and controlled biodegradability.
- **Sweetener proteins** such as brazzein, monellin, and thaumatin function as high-intensity sweeteners, more than a thousand times sweeter than sucrose.
- **Serum albumin** is used for drug delivery, cell culture, and diagnostic reagent applications.

Conventional supply chains face mounting pressure. Dairy and egg production contends with volatility from avian and swine flu and from climate impacts on pasture. Supply security concerns extend to strategic food autonomy—a priority for regions like the Middle East—as well as overfishing pressures on seafood-derived proteins and mercury contamination risks.

Price volatility compounds the challenge: dairy and egg ingredient prices fluctuate sharply, making cost-parity calculations for any alternative inherently uncertain. Conventional extraction also has structural limitations, including allergen content (lactose and egg proteins), animal welfare considerations, and significant greenhouse gas emissions, water use, and land-use footprints.

The biological case for non-catalytic proteins rests on demonstrated functional parity combined with meaningful performance advantages. Beta-lactoglobulin produced via precision fermentation has proven that biology can match dairy protein functionality. Fermentation also offers compositional control (no lactose or fat) and the ability to tailor mineral binding, foaming, and emulsification properties through sequence variants. Texture, flavor, color, and taste meet or exceed conventional benchmarks. Crucially, biology offers design freedom: engineers can optimize for function rather than simply copying nature.

By decoupling production from livestock volatility and disease outbreaks that periodically disrupt conventional supply, the biological production of non-catalytic proteins offers supply chain resilience. Environmental benefits are significant, with potential for major reductions in greenhouse gas emissions, water use, and land use compared to agricultural extraction.

Perhaps most compelling is the potential for multifunctionality: a single engineered protein could provide gelling, foaming, and other properties simultaneously, with egg proteins serving as the natural benchmark for integrated functionality.

Economic viability

Current economics favor precision fermentation in select applications.

Cost-in-use is already competitive for infant and sports nutrition grades, where purity requirements and functional specifications justify premium pricing. At commercial scale, functional proteins command 50–60% premiums over commodity proteins, creating headroom for fermentation-based alternatives to achieve cost competitiveness[31].

The clearest economic wins emerge where microbial proteins can be used with minimal

[30] Market sizing draws on data from the Good Food Institute, Technavio, GM Insights, and Grand View Research, as synthesized in the AB4S Priority Molecule Group Fact Pack, December 2025.

[31] AB4S Workshop Synthesis, November 25, 2025. Unpublished.

purification, avoiding the DSP burden that erodes margins in other molecule families.

The strategic question is where to play. Pure nutrition proteins face a difficult value proposition: commodity soy and pea protein trade at approximately $1 per kilogram, and the sustainability narrative alone does not justify the cost gap for drop-in replacements.

Functional proteins tell a clearer story:

- In food, they address health and functionality demands.
- In cosmetics, they offer novel, green-by-design ingredients with performance levels that conventional actives cannot match.
- In pharma, they serve as performance ingredients with defined specifications.

The strategic focus should be on functional proteins across food and non-food applications, where differentiated performance justifies investment in pricing and qualification. The commodity protein market can wait.

Technical & Infrastructure Reality

Technology readiness for non-catalytic proteins spans the full industrial spectrum, moving from proven commercial assets to high-potential pilot programs.

- Beta-lactoglobulin has reached commercial production.
- Silk proteins are also commercial.
- Alpha-lactalbumin, casein, and ovalbumin sit at demonstration and pilot scale.
- Lactoferrin and sweetener proteins are advancing toward commercialization.

The active start-up landscape spans all categories:

- Animal-free dairy proteins: Perfect Day, Remilk, New Culture, Imagindairy, Standing Ovation, and Those Vegan Cowboys
- Silks: Bolt Threads and AMSilk
- Sweetener proteins: Oobli and Amai
- Egg proteins: The EVERY Company and Onego Bio
- Diverse protein portfolios spanning multiple applications: 21st.BIO and Geltor

This list is illustrative. The broader start-up landscape continues to grow and innovation continues to advance. For example, Solar Foods' Solein, a single-cell protein produced via gas fermentation from CO_2, hydrogen, and electricity rather than conventional feedstocks, represents an emerging production approach that extends the non-catalytic protein category beyond precision fermentation of known sequences[32].

Production challenges are real but understood. Low yield and DSP efficiency affect most proteins in the family. Protein instability and susceptibility to degradation complicate both fermentation and downstream processing. Sterility issues frequently arise at scale.

Specific molecules present hurdles: lactoferrin is a large, complex glycoprotein that proves difficult to purify and struggles to reach commercial titers. Alpha-lactalbumin suffers from low titer and strain instability. Brazzein, despite being a small protein, requires specific structural forms to function as a sweetener.

Technical advantages offset these challenges. Protein sequences can be modified quickly, allowing engineers to design for function rather than replicate nature exactly.

Downstream processing is relatively straightforward compared to many small molecules produced by precision fermentation, a meaningful advantage given that DSP typically dominates production costs.

Established precedents from enzyme producers such as DSM, IFF, Lallemand, and Novonesis demonstrate that proteins can be manufactured at reasonable cost. Protein design tools from Arzeda, Basecamp Research, Biomatter, Cradle, Profluent, and Shiru, among others, combined with existing literature, can deliver an estimated 80% of the needed functionality before any bespoke development begins. Once a platform organism is optimized for one protein, expansion to adjacent proteins accelerates the pipeline.

Infrastructure requirements place non-catalytic proteins in the same category as terpenes and peptides. New dedicated capacity will be essential. DSP complexity

[32] Solar Foods. Solein®. https://solarfoods.com/solein/. Accessed February 2026.

depends on purity requirements and market specifications rather than product class: terpene purification can be simple (oil-water separation) or complex (99% purity targets). The same applies to proteins. Where specifications allow, modular facility designs can aggregate demand across product categories.

This family is not brownfield-compatible in the way hydroxy acids can bolt onto existing chemical infrastructure. Improved filtration and drying capabilities are required, though some brownfield compatibility may be achievable for specific applications. US policy funding and growing industrialization know-how are improving scale prospects, but the capital path remains longer than for molecules that can leverage existing facilities.

Regulatory Landscape

Regulatory pathways diverge sharply by geography. In the United States, the Generally Recognized as Safe (GRAS) pathway for foods is well-established, although recent policy proposals and growing scrutiny are reshaping how self-affirmed GRAS determinations are viewed[33] [34]. Several proteins have successfully navigated this route, including beta-lactoglobulin from Perfect Day.

Europe presents a more challenging environment. No precision fermentation proteins have yet been authorized under Novel Foods regulations. The use of genetically modified materials is strictly regulated. Limited financing compounds these regulatory headwinds.

Other jurisdictions are charting their own courses. Israel has approved specific dairy proteins, with Remilk receiving authorization. This regulatory divergence shapes market entry strategy: companies may need to sequence launches based on where approvals can be secured first.

Labeling presents its own complications. Dairy-identical claims must align with local regulations. In some geographies, calling fermentation-derived products "milk" regardless of molecular identity is prohibited. Similar debates are unfolding around "meat" alternative labeling in the EU. For food applications, the central challenges are positioning and pricing: how to communicate the value proposition to consumers in a regulatory environment that constrains terminology while competing with lower-cost conventional alternatives.

What It Takes to Succeed

Near-term priorities should center on functional proteins with clear differentiated value rather than commodity nutrition plays.

The path forward involves mapping specific problem areas, where functional proteins offer solutions that justify qualification investment, such as sugar reduction and allergen-free formulations.

Business models should be partnership-led:

> The strategic focus should be on functional proteins across food and non-food applications, where differentiated performance justifies investment in pricing and qualification. The commodity protein market can wait.

co-developing stories and proof-of-concept demonstrations with customers rather than building capacity and hoping demand follows. Sweet protein pilots exemplify this approach, with companies asking potential customers directly, "Can we build the story with you?"

Application priorities span multiple sectors.

- In food, sweet proteins offer high potential if aftertaste challenges can be resolved, anti-freeze proteins are advancing toward commercialization, and functional ingredients such as patatin show promise.

[33] HHS targeting GRAS "loophole" for rule making: What Food companies need to know. Gardner. 27 March 2025. https://gardner.law/news/hhs-targets-gras-loophole

[34] Food and feed ingredients and additives in the United States: is the self-affirmed GRAS pathway coming to an end. Medfiles Group. 29 January 2026. https://medfilesgroup.com/food-and-feed-self-affirmed-gras-pathway/

- In cosmetics, the opportunity lies in novel, green-by-design proteins that deliver performance levels conventional actives cannot match, with anti-aging applications through proteins like elastin. among the most promising.
- In materials, silk proteins, fibers, and protein-based leather are gaining traction. For example, automotive OEMs are already working with companies like Modern Meadow on interior applications.

The longer-term vision centers on building a shared platform ecosystem. Standardizing functionality testing and application development protocols would reduce development time, costs, and uncertainty across the industry. For Europe specifically, this represents an opportunity to establish leadership despite current regulatory constraints, positioning for the eventual market opening.

Recommendations

Non-catalytic proteins raise strategic questions that no single company can resolve on its own. *Who should focus on discovery: technology developers, ingredient companies, or end-use brands? Should a dedicated organization be created specifically for protein innovation? And critically, should discovery be pushed to customers or pulled by a central coordinating entity?*

Coordinated action could unlock value across several dimensions by:

- Stimulating protein discovery by defining which proteins merit collective focus, rather than leaving prioritization to fragmented market signals,
- Coalescing demand and piecing together the value chain through binding commitments, for example "we buy if…" statements, gives producers confidence to invest in capacity. For food proteins specifically, a single offtake is rarely sufficient: a broader customer portfolio across applications and geographies reduces concentration risk and creates more durable demand signals.
- Utilizing shared facilities for pilot production and application testing, reducing the capital burden on individual players,
- Identifying customer needs systematically to align discovery efforts with real market pull, and
- Combining in silico modeling with high-throughput screening to accelerate molecule prioritization and reduce wet-lab iteration cycles.

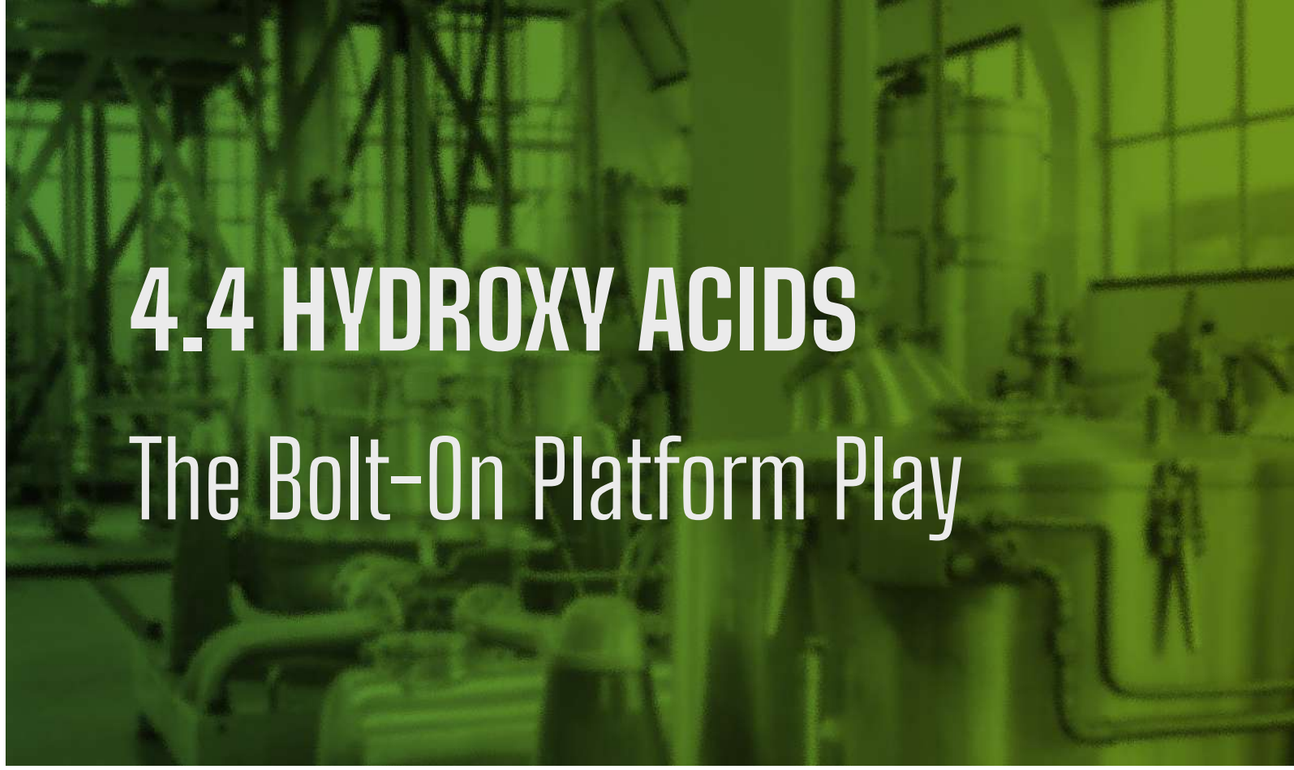
Several proof points are already commercial or near commercial. Beta-lactoglobulin is in the market through Perfect Day. Casein for mozzarella applications is advancing via New Culture. Sweet proteins from Oobli and Amai represent low-volume, high-margin opportunities. Collagen analogs for cosmetics, like those offered by Geltor, for cosmetics address the growing demand for animal-free formulations. Functional egg replacements from The EVERY Company and Onego Bio target supply chain volatility exposed by recent avian flu outbreaks.

Market Realities

Europe faces structural hurdles: limited financing, Novel Foods authorizations that can take up to 36 months, and a cautious regulatory environment for precision fermentation proteins.

Consumer acceptance of GMO alternatives is low in EU markets. True multifunctionality in a single protein remains technically difficult. And commodity protein parity at $1/kg is out of reach without premium positioning or regulatory tailwinds.

The functional protein strategy sidesteps some of these risks by competing on performance rather than cost, but execution requires disciplined focus on applications where differentiation justifies the investment.



4.4 HYDROXY ACIDS

The Bolt-On Platform Play

Commercial Case

Hydroxy acids occupy a unique position among the four priority molecule families: They represent the clearest pathway to large-scale volumes through the integration of existing chemical infrastructure, rather than purpose-built biomanufacturing facilities.

The market opportunity is substantial. Excluding already-commoditized citric and lactic acid, the hydroxy acids market reaches approximately $1.8–2 billion annually and is growing at nearly 9% per year, with demand of 260–320 kilotons.

But the real prize lies in downstream derivatives.

Acrylic acid alone represents a 7-million-ton market. Nylon precursors add another 4 million tons.

Unit prices range from $2–15 per kilogram, with tartaric and malic acids at the lower end and mandelic acid commanding premium pricing for pharmaceutical and cosmeceutical applications.

End-markets span multiple sectors:

- Food and beverage: acidulants, flavoring agents, and antioxidants
- Home and personal care: chelates, builders, and alpha-hydroxy acid exfoliants
- Polymers: the largest volume opportunity, with lactic acid serving as the precursor for polylactic acid (PLA), while 3-hydroxypropionic acid (3-HP) feeds into acrylic acid production for superabsorbent polymers and CASE acrylates

- Construction: tartaric acid as a cement retarder
- Solvents: levulinates for coatings, electronics, cosmetics, and pharmaceuticals

Potential customers include major consumer goods companies, coatings manufacturers, chemical intermediaries, and acrylics and SAP suppliers.

The molecule family divides into established and emerging bio-routes. Citric and lactic acid production via fermentation is fully commoditized, representing multi-billion dollar markets that demonstrate biology works at an industrial scale.

3-HP is a key platform molecule: it converts to acrylic acid via dehydration, unlocking superabsorbents, coatings, and adhesives. Levulinic acid opens a separate pathway to γ-valerolactone (GVL), plasticizers, solvents, and fuel and polymer intermediates. Specialty molecules, including malic acid, mandelic acid, and tartaric acid, address higher-value niches in food, pharmaceuticals, and cosmeceuticals.

Conventional production routes carry significant drawbacks. Petrochemical synthesis involves multi-step processes that are energy-intensive and subject to feedstock price volatility. Some routes require hazardous reagents: cyanides for mandelic and malonic acid production, maleic anhydride derivatives for others.

The existence of successful bio-routes for citric and lactic acid demonstrates that fermentation can compete at scale. However, novel molecules like 3-HP and levulinic acid still face a cost gap with entrenched petrochemical incumbents.

The biological case for hydroxy acids differs fundamentally from the other priority molecule families. There is no real performance advantage. These are drop-in replacements that must compete on cost.

The value proposition rests on several advantages over conventional routes:

- Sustainability marketing for consumer-facing products like diapers and athletic wear
- Process safety improvements that eliminate hazardous reagents
- Stereochemical control for pharmaceutical and cosmeceutical applications
- Cleaner production with fewer heavy-metal or solvent residues
- Supply chain resilience, particularly in regions like the EU where limited domestic fossil precursors make on-shoring bio-based production strategically compelling

The existence of successful bio-routes for citric and lactic acid demonstrates that fermentation can compete at scale.

In cosmetics specifically, hydroxy acids offer controlled exfoliation and humectancy, with the ability to tune molecular properties for gentleness. Sensory constraints limit some applications: sourness and odor restrict inclusion levels in food and beverage products and often require masking.

Current economics favor petrochemical production. Bio-based routes remain more expensive today, though the gap varies significantly by molecule and scale.

Industry participants believe cost parity is achievable within 5–10 years through scale-up and strain optimization. Importantly, customer interest already exists. There is a strong market pull for bio-acrylics and bio-acrylates, particularly in diaper applications where sustainability claims resonate with consumers.

Technical and Infrastructure Reality

Technology readiness varies across the hydroxy acid family.

- Citric acid, lactic acid, succinic acid, and tartaric acid are fully commercial.
- 3-HP has reached demonstration and pilot scale through work by Cargill, BASF, Novonesis, and LG Chem. In 2025, LG Chem announced that it was accelerating the commercialization of 100% plant-based acrylic acid produced from fermented 3-HP, beginning with prototype production of about 100 metric tons per year[35].
- Levulinic acid and bio-mandelic acid remain in earlier development stages.

Production challenges are significant but understood.

- The greater challenge for 3-HP lies in reaching yields approaching 90% of theoretical, a benchmark that recent high-performance strains have nearly achieved[36, 37]. AI-guided optimization can help close the remaining gap.
- Organic acids are inherently toxic to microbial cells, requiring careful pH control. Subsequent neutralization creates an ion exchange burden in downstream processing.
- Strains tend to produce biomass and byproducts (glycerol is a common culprit), which harms both economics and purification.

When hydroxy acids serve as building blocks, additional process steps are required to convert them to final products (3-HP to acrylic acid, for instance), adding cost in a business where margins are already thin.

The infrastructure story is where hydroxy acids diverge most sharply from the other priority molecules.

This family represents the clearest brownfield opportunity: production can integrate into existing chemical value chains rather than requiring investment in building new biomanufacturing facilities. Existing fermentation capacity could be repurposed, improving capital efficiency. The "one plant, multiple products" platform logic applies here, and earlier integration into chemical platforms increases synergy potential.

Cost drivers for hydroxy acids differ from those of high-value molecules. Downstream processing is not the universal bottleneck for this family. Feedstock cost and biological conversion efficiency matter equally or more. Feedstock must be both low-cost and reliable. Supply security matters as much as price. Sugar quality is critical: polymer applications demand 99.9% purity with very low color, requiring clean feedstock rather than complex waste streams.

Capital requirements remain substantial—hundreds of millions of dollars, even for brownfield integration. This assumes high-yielding strains are available. Strain optimization to achieve those yields remains an active challenge for several molecules.

[35] LG Chem. LG Chem accelerates commercial production of 100% plant-based acrylic acid. 13 February 2025. https://www.lgcorp.com/media/release/28661
[36] Qin N. et al. Increased CO2 fixation enables high carbon-yield production of 3-hydroxypropionic acid in yeast. Nature Communications. 21 February 2024. https://www.nature.com/articles/s41467-024-45557-9
[37] Bhagwat S. et al. Sustainable production of acrylic acid via 3-hydroxypropionic acid from lignocellulosic biomass. ACS Sustainable Chemistry & Engineering. Vol 9/Issue 49. 29 November 2024. https://pubs.acs.org/doi/10.1021/acssuschemeng.1c05441

What It Takes to Succeed

With hydroxy acids, three factors are critical.

- Achieving economies of scale is non-negotiable. The target price of $1–1.5 per kilogram for acrylates leaves no room for subscale production.
- Feedstock supply must be secured at low cost with long-term reliability.
- Integration into existing chemical infrastructure rather than greenfield construction is essential to manage capital intensity.

Near-term priorities center on de-risking. Securing offtake agreements or take-or-pay commitments from downstream customers, such as multinational CPGs, that can underwrite capital investment. Demonstration plants are crucial for showcasing yield and rate performance that creates a believable cost model for investors. Retrofitting existing empty fermentation capacity (for example, the approach taken by BlueStem Bio) can accelerate timelines. Strain engineering, increasingly guided by AI-enabled pathway design and predictive modeling, must continue pushing toward theoretical yield limits.

Longer-term, the pathway leads to the production of next-generation sugars or waste carbon streams to improve feedstock economics, and to modular plant designs that reduce capital intensity.

Workshop participants identified a collective target: $1 billion in bio-acid revenue within 5 to 10 years across multiple partners, with returns expected over a 10 to 15 year horizon. A concrete milestone would be one additional bio-acid reaching 100 kiloton scale.

Recommendations

Hydroxy acids exemplify why coordination matters more than innovation for the deployment of industrial biotechnology. The technical innovation already exists: Cargill, BASF, Novonesis, and LG Chem have demonstrated the core technology. The challenges are pricing, demand aggregation, and multi-market integration.

Coordinated action can unlock value that no single player could capture on their own. Demand aggregation through industry consortia can provide the market signal needed to justify capital investment and share risk across participants. Large customers can baseload a plant. A single product line or a single customer can underwrite the CapEx required to make scale economics work. Partnerships must extend both downstream to customers and upstream to feedstock suppliers for long-term supply security.

The most promising near-term opportunities include:

- 3-HP to acrylic acid, where the superabsorbent polymer and diaper applications offer concentrated demand and strong customer pull.
- Mandelic acid for pharmaceutical and cosmeceutical applications, where it can replace hazardous synthetic routes.

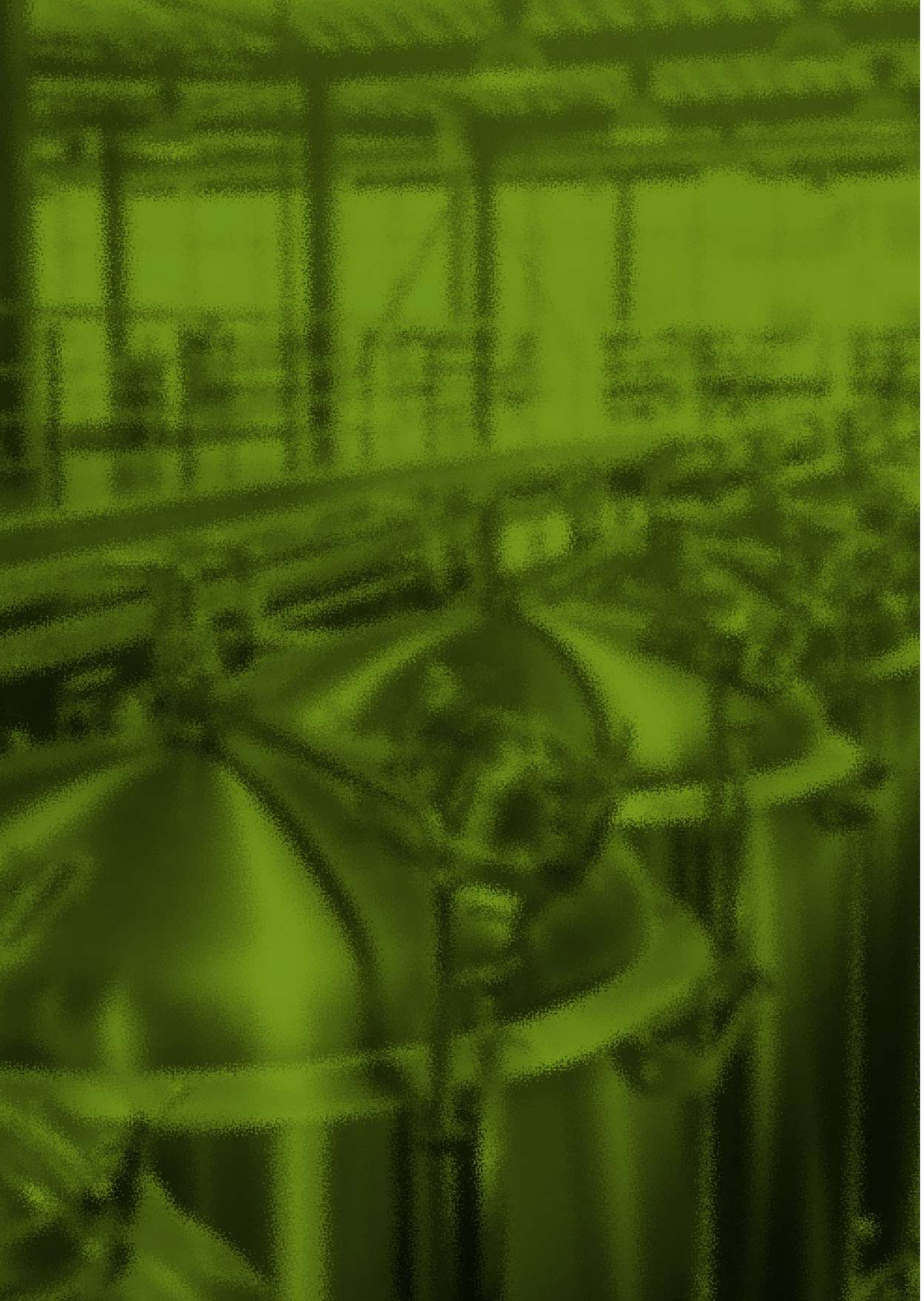
Market Realities

Petrochemical incumbents set commodity price floors, and commodity applications show high price sensitivity. Some markets (solvents) are large but fragmented, making demand aggregation difficult.

The 2010s provide cautionary lessons. Succinic acid attracted significant investment and multiple well-funded entrants, including BioAmber, Myriant, and others, but the molecule itself proved to be the problem: limited downstream utility, insufficient performance advantages over petrochemical intermediates, and a market that never developed the pull needed to justify the capital required. The failures were less about execution than about selecting a molecule where bio-based routes could not establish a durable advantage.

For commodity molecules, where competition turns entirely on cost, delayed action in the US and EU risks ceding the market to producers who achieve scale economics first. This is not a performance differentiation play. Success depends entirely on cost competitiveness and the ability to coordinate across a complex value chain before structural advantages consolidate elsewhere.

> Current economics favor petrochemical production. Bio-based routes remain more expensive today, though the gap varies significantly by molecule and scale.



5. ENABLING CONDITIONS FOR SCALE

The molecule analyses in Section 4 reveal common requirements that cut across all four priority families. This section synthesizes those enabling conditions into actionable priorities for infrastructure, technical capabilities, market development, regulatory alignment, and collaboration.

Infrastructure Strategies

The two deployment tracks identified in Section 2 (bolt-on versus build new) have direct infrastructure implications.

Terpenes, peptides, and non-catalytic proteins generally require dedicated fermentation and downstream processing facilities, though existing enzyme plants may be adaptable for functional proteins. Existing CDMO and CMO capacity can serve early production needs, and multipurpose facilities designed for flexibility across product families improve capital efficiency.

Hydroxy acids can integrate with existing chemical value chains rather than requiring purpose-built biomanufacturing facilities. Existing fermentation capacity could potentially be repurposed, but commodity-scale volumes still demand substantial capital investment given the prices set by petrochemical incumbents. Success depends on partnerships with chemical platform operators who control the downstream infrastructure.

The key is deliberate clustering: grouping molecules with similar DSP requirements (oily products, proteins, similar chain lengths) so that one facility can serve multiple markets and shift between applications as economic conditions change.

Hybrid bio-chemical routes offer the fastest path to competitiveness for certain molecules. Combining fermentation with downstream chemistry (3-HP fermentation followed by dehydration to acrylic acid, or the MVA pathway plus chemistry for isoprene) can shorten pathways and improve yields. These approaches are most applicable to hydroxy acids and some

terpenes, less so for peptides and proteins, where biological production captures the full value proposition. Hybrid routes require careful lifecycle assessment. The sustainability case depends on the full process, not just the fermentation step.

Technical Capabilities

Downstream processing is frequently cited as the universal bottleneck in biomanufacturing, but this generalization requires nuance.

For high-value, low-volume molecules (peptides, non-catalytic functional proteins, specialty terpenes), DSP is indeed 30–40% of operating costs and heavily influences capital requirements. Learnings from pharma on separation technology, in-situ product removal, and smarter filtration can drive meaningful cost reduction.

For commodity-scale molecules like hydroxy acids, feedstock cost and bioconversion efficiency matter equally or more.

The strategic implication: cost-reduction priorities must be set molecule by molecule, not assumed from general principles.

The strategic implication: cost-reduction priorities must be set molecule by molecule, not assumed from general principles.

Continuous biomanufacturing offers advantages over traditional batch methods: higher productivity, reduced costs, smaller facility footprint, and more consistent product quality. Automated, real-time process control minimizes downtime and waste while enabling faster delivery of molecules and greater flexibility. For molecules where capital intensity is a barrier, continuous processes can improve the economies of scale. Realizing these benefits, however, requires strains stable enough to maintain performance over extended runs. Such strains are not always easy to engineer, particularly at high yields.

AI-enabled design is accelerating development across all molecule families, not just peptides and proteins.

For sequence-based molecules, AI tools combined with high-throughput screening compress the cycle from molecule definition through expression characterization to application prioritization. AI-driven enzyme and strain-engineering platforms, originally proven in protein and biocatalyst optimization, are now routinely applied to small-molecule pathways, including terpenoids and other oxygenated organic acids, demonstrating that these tools confer comparable benefits beyond protein products[38]. Process optimization through self-driving labs, digital twins, and retrospective batch analysis can also improve yields and reduce variability across the board[39].

The practical near-term application may be AI interfaces that help application scientists identify which culture conditions, processing steps, and strains deliver target properties—taking development timelines from years to months.

Beyond discovery and development, AI contributes to the cost reduction trajectory that underpins every molecule in this report. Predictive process control improves batch-to-batch consistency, reducing waste and improving facility utilization. As production data accumulates across facilities and molecule families, these tools create compounding learning effects, the same platform logic that drives biological costs lower, applied to the manufacturing process itself.

Standardization must extend beyond assays and specifications to the production process itself. If physical facilities are designed to comply with process standards, the need for product-by-product optimization diminishes.

An industry-wide toolbox of biotech synthesis and process steps (analogous to what major enzyme producers maintain internally) would allow faster development and more predictable scale-up. This includes standardized terminology, analytical techniques, and test methods that enable meaningful comparison across companies and products.

Shared application labs could reduce qualification timelines that currently stretch 12–36 months. Application testing often

[38] Khan M. et al. AI-driven enzyme engineering: emerging models and next-generation biotechnological applications. Molecules. 22 Dec 2025. doi: 10.3390/molecules31010045.
[39] Rupnow C et al. A self-driving laboratory optimizes a scalable process for making functional coatings. Cell Reports Physical Science. 17 May 2023. https://doi.org/10.1016/j.xcrp.2023.101411.

requires only milligram-scale volumes, while the discovery phase can be supported through chemical synthesis routes before committing to biological production at scale. Shared facilities keep costs down during capital-intensive early stages and allow multiple players to validate performance without duplicating infrastructure.

Market Development

The central lesson from Section 2: demand validation must precede infrastructure investment. Supply-side innovation without anchored demand produced the failures of the 2010s. Each molecule must have customers ready to buy at prices that work before capital is committed to production capacity.

Binding offtake commitments change the economics of scale-up. "We buy if..." statements put skin in the game. Take-or-pay agreements de-risk capital investment by providing revenue certainty. A single large customer can baseload a plant, with one product line or one major CPG underwriting the CapEx required for scale economics to work.

The practical implication: procurement standards focusing on cost reduction and supply diversification do not work for the supply of such innovative molecules at this stage of development. These supply decisions should involve C-level teams with dedicated and independent budgets.

Industry roadmap co-creation accelerates qualification cycles by aligning technology developers with downstream users early. Co-development partnerships—building the story and proof of concept together rather than hoping customers materialize—can compress the time from demonstrated functionality to commercial traction. This approach requires motivating both consumers (who create pull) and manufacturers (who must reformulate and qualify) in parallel.

Regulatory Alignment

Regulatory pathways vary significantly by geography and molecule type, creating both barriers and opportunities.

In the United States, the GRAS pathway is well-established for food peptides and proteins, with several precision fermentation products having successfully navigated approval. EPA registration for biopesticides like nootkatone provides a clear path for agricultural applications. The regulatory environment generally favors innovation, though the GRAS framework is under active scrutiny: FDA's proposed rule to eliminate the self-affirmation pathway and require mandatory notification, currently under regulatory review, could increase the time and cost of bringing new food ingredients to market. Companies relying on self-affirmed GRAS determinations should monitor this closely.

Europe's process-based regulatory framework creates a structural barrier: fermentation-derived ingredients can be subject to GMO-related restrictions even when the final molecule is chemically identical to conventionally produced alternatives. A shift toward product-based frameworks aligned with approaches in the US and Latin America would improve market access for the molecules in this report.

Regulatory restrictions on PFAS are driving demand for innovation in peptide production, with biotechnology offering viable alternatives that meet both performance and compliance requirements.

Beyond specialty markets, for large-volume, low-cost commoditized products where drop-in substitution is the goal, regulatory mandates are equally critical in driving the switch to renewable alternatives. The Renewable Energy Directive (RED) for biofuels and the growing Sustainable Aviation Fuel (SAF) mandates demonstrate how policy-driven demand can accelerate commercial deployment at scale.

Collaboration Models

The historical mismatch in industrial biotechnology is structural: investment needs sit with innovative technology providers and startups, while risk-carrying ability sits with large corporations. Collaboration models must bridge this gap.

Partnerships with strategic customers can de-risk development by securing commitment before scale-up. Reasonable production costs are achievable when strategic customers are engaged from the start. Business models should be partnership-led, co-developing with committed customers rather than building capacity and hoping demand follows.

Shared infrastructure consortia spread FOAK risk across participants. The Danone-DMC-Michelin-Crédit Agricole biotechnology platform exemplifies how cross-industry collaboration can fund shared facilities. The Circular Bio-based Europe Joint Undertaking (CBE JU) flagship projects are explicitly designed to achieve this[40]. Notable successes include the world's largest mycoprotein facility in the Netherlands[41] and Europe's first industrial-scale microalgae biorefinery in France[42]. CBE JU projects leverage €2.80 in private investment for every €1 of public funding, demonstrating that well-structured public-private consortia can unlock the capital required for FOAK facilities[43]. Partnerships between CDMOs/CMOs and corporations enable multipurpose facilities that serve multiple companies without requiring each to build dedicated capacity.

IP pooling and cross-licensing, with standard terms analogous to IT hardware standards, could accelerate development by reducing friction over freedom to operate. Shared IP libraries with base information on licensable strains would allow technology players to build products and applications without reinventing foundational work. Early-stage IP sharing agreements help startups protect their innovations while enabling licensing and joint development with manufacturing partners.

Platform-oriented ecosystems may be necessary for peptides and proteins, where discovery is fragmented, and no single company can resolve strategic questions alone. The open questions raised in Section 4—who leads discovery, whether dedicated organizations are needed, and how to balance push and pull models—apply across both families.

The answers to these questions will shape how quickly the industry moves from fragmented experimentation to coordinated scale.

Workforce and Talent

Scaling biomanufacturing requires a workforce that does not yet exist at sufficient scale. The industry competes with pharmaceutical companies that offer higher salaries and greater stability, and the talent pipeline for industrial biotechnology remains underdeveloped globally.

But the talent gap is not only a competition for PhDs. Industry workforce analyses indicate that a substantial share of biomanufacturing roles can be filled by workers with sub-bachelor's credentials, often through community college or technical training programs, with one national study finding roughly one-third of biotech workers in middle-skill positions requiring more than high school but less than a four-year degree[44]. In addition, workers from legacy manufacturing, energy, and agricultural industries bring transferable skills that align closely with biomanufacturing operations.

Workforce development programs, industry retraining pathways, and stronger ties between academia and commercial operations are enabling conditions on par with infrastructure and regulation—and they must scale in parallel with production capacity.

Geography and Supply Chain

Infrastructure geography creates strategic choices.

[40] Mission and Objectives. Circular Bio-based Europe. https://www.cbe.europa.eu/mission-and-objectives
[41] Flagship biorefinery makes much needed non-animal protein. Circular Bio-based Europe. 16 October 2023. https://www.cbe.europa.eu/achievements/flagship-biorefinery-makes-much-needed-non-animal-protein
[42] CBE JU's 2025 in review. Circular Bio-based Europe. 22 December 2025. https://www.cbe.europa.eu/news/cbe-jus-2025-review
[43] Achieving sustainable competitiveness: CBE JU's main contribution to the EU Green Deal. Circular Bio-based Europe. 14 September 2023. https://www.cbe.europa.eu/news/achieving-sustainable-competitiveness-cbe-jus-main-contribution-eu-green-deal
[44] Innovation of the biopharmaceutical manufacturing workforce. Center for Structured Biotechnology Innovation (CSBI). 2022. https://innovatebio.org/sites/default/files/blog-attachments/biomanufacturing-workforce-10-2022.pdf

Europe faces high energy costs and a slower regulatory environment, but it possesses a strong chemical infrastructure for brownfield integration.

The United States leads in frontier biotechnology and benefits from faster regulatory paths and initiatives like BioMADE, but coordination challenges remain in translating lab breakthroughs to commercial production.

China has emerged as a formidable force in biomanufacturing, combining state-backed investment, lower production costs, and rapidly scaling capacity across multiple molecule categories.

India is rapidly building industrial biotechnology capabilities, with the BioE3 policy and associated biomanufacturing hubs expanding fermentation-based production capacity and attracting increasing government and private investment into the sector[45].

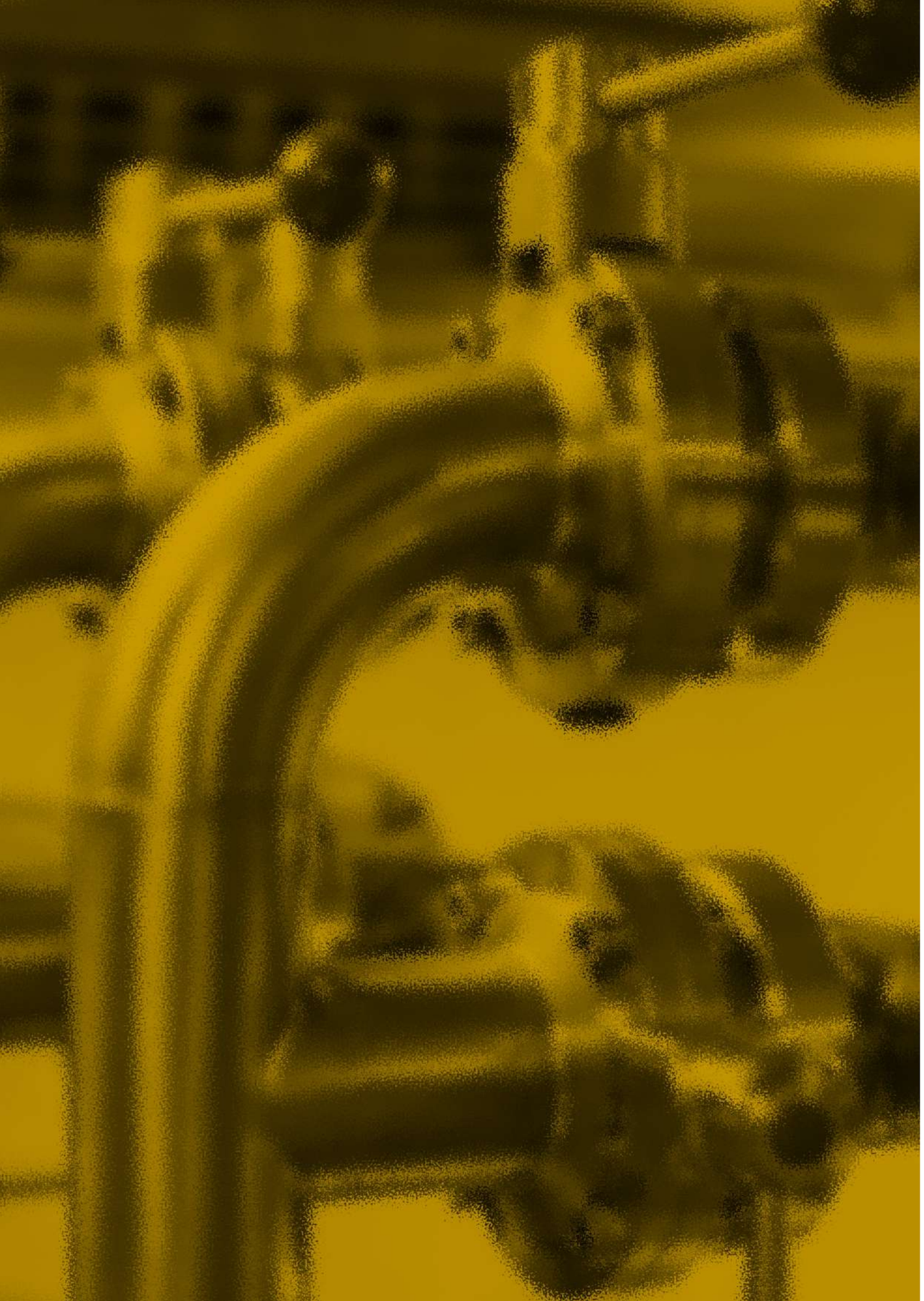
Regionalized manufacturing makes strategic sense when feedstock security, supply chain resilience, or regulatory requirements favor local sourcing. Global partnerships make more sense for commodity molecules where cost is everything, and access to low-cost energy or feedstock regions determines competitiveness. The feedstock strategy should not dogmatically favor second-generation (2G) over first-generation (1G) sources. 1G feedstocks are acceptable where cost and efficiency win. That said, sugar quality remains critical for polymer applications requiring high purity.

Lessons from Past Failures

Three patterns recur in biomanufacturing failures.

1. DSP costs are determined in the design phase but incurred at the end of the process. Upstream choices about organisms and pathways heavily influence scaling potential. Yet this connection is often neglected until it is too late to change course.
2. Insufficient demand aggregation leaves companies with capacity but not customers. Offtake requirements must be large enough to justify new plants, and small volumes from individual customers rarely suffice.
3. Economic and timeline mismatches persist. Margins are lower than startups expect. The green premium is unreliable. And ten-year-plus timelines conflict with typical investor horizons. Matching biotech investments with capital structures suited to risk profile—family offices, infrastructure investors, FOAK/SOAK loan guarantee programs—addresses part of this mismatch. Still, realistic expectations must be set from the start.

[45] Fostering High-Performance Biomanufacturing. Biotechnology Industrial Research Assistance Council. 24 August 2024. https://www.birac.nic.in/biomanufacturing.php



6. THE PATH FORWARD

Four molecule families offer validated demand and credible paths to scale. Translating that potential into deployment requires coordinated action across stakeholders. This section provides the operational framework.

Executive Playbook

For Downstream Users and CPG Brands

- **Commit early.** Binding offtake agreements de-risk capital investment and unlock scale economics. A single large customer can baseload a plant. "We buy if..." commitments at specified price and volume levels give technology developers the market signal needed to justify CapEx.
- **Co-develop, don't wait.** Qualification cycles of 12-36 months mean that brands waiting for finished products will trail competitors who engaged early. Joint development agreements compress timelines and ensure molecules meet application requirements. Partnership-led models will outperform supply-led approaches.
- **Build startup-corporate collaboration.** Traditional vendor relationships leave value on the table. Structured co-innovation partnerships (with clear IP frameworks, milestone-based funding, and shared risk) enable startups to access scale and corporates to access innovation. The European Innovation Council's 2025 report on corporate-startup collaboration provides a framework for these mechanisms[46].
- **Raise decisions to the C-suite.** Supply decisions made by procurement teams optimize for cost. Decisions made by marketing and C-level teams can capture strategic value. Bio-based ingredients increasingly drive brand differentiation. Treat sourcing

[46] European Innovation Council publishes flagship report on corporate-startup collaboration. European Innovation Council. 10 July 2025. https://eic.ec.europa.eu/news/european-innovation-council-publishes-flagship-report-corporate-startup-collaboration-2025-07-10_en

as a strategic capability, not just a cost center.

For Investors

- **Match capital to risk profile.** Industrial biomanufacturing sits between venture and infrastructure risk. Too long for traditional VC. Too uncertain for project finance. Blended structures that combine equity for innovation with debt and strategic capital for scale can bridge this gap. Expect step-function growth with plateaus, not hockey-stick trajectories.
- **Think like project finance.** The capital stack for a biomanufacturing facility should look more like infrastructure than software. Equity catalyzes innovation and initial traction. Scaling production requires project finance, debt, and strategic capital. Structure deals so that one dollar of equity leverages three to five dollars of other capital.
- **De-risk sequentially while prioritizing commercial resilience.** Projects that solve unmet needs with positive economics from the start should be prioritized. While blended funding and loan guarantees mitigate risk for FOAK and SOAK facilities, the primary catalyst for private investment remains a clear, profitable market pull independent of long-term subsidies.

For Policymakers

- **Streamline regulatory pathways by recognizing biotechnology's 50-year safety record.** Harmonizing US GRAS and EU Novel Foods processes across regions reduces compliance burdens. A shift toward product-based regulatory frameworks would prevent market distortions in which companies are forced to adopt more costly, inefficient production methods to avoid regulatory restrictions on inactivated biomass that contains no living modified organisms.
- **Support FOAK infrastructure.** FOAK commercial plants carry disproportionate risk. Loan guarantee programs, tax incentives for domestic biomanufacturing, and co-investment in shared pilot facilities can catalyze private capital. BioMADE and similar initiatives demonstrate the model.
- **Create demand-side pull.** Public procurement preferences, bio-based content incentives, and sovereignty mandates can create guaranteed market access that de-risks private investment. Supply-side support alone is insufficient without anchored demand[47,48].
- **Coordinate national strategy.** China's biomanufacturing strategy goes beyond company support. It's a comprehensive industrial policy including priority molecule selection, investment in regional biomanufacturing hubs, and coordinated scale-up across 43 companies by 2027[49]. European and US responses require similar coordination to avoid ceding strategic capability in a sector with implications for food security, materials supply chains, and economic resilience.
- **Invest in workforce development.** Biomanufacturing workforce needs extend beyond research scientists to process engineers, fermentation operators, and plant technicians. Community college programs, industry retraining pathways for workers transitioning from legacy manufacturing and energy sectors, and stronger academic-industry partnerships can build the talent pipeline that production capacity will require.

[47] Scaling up Europe's bio-based industries. European Investment Bank. 31 October 2025. DOI: 10.2867/3037662, https://www.eib.org/en/publications/20250060-scaling-up-europe-s-bio-based-industries
[48] Innovative financing mechanisms for alternative proteins in Europe. GFI Europe. May 2025. https://gfieurope.org/resource/innovative-financing-mechanisms-for-alternative-proteins-in-europe/
[49] Van Der Kley D. China releases list of 43 companies to build biomanufacturing pilot plants. BioBrawl. 19 November 2025. https://dirkvanderkley.substack.com/p/china-releases-list-of-43-companies

Molecule-Specific Priorities: A Call to Action for the Industry

Terpenes: Fastest Commercial Wins

STAKEHOLDER	PRIORITY ACTION	TIMELINE
Flavor & fragrance houses	Aggregate terpene demand across buyers to baseload shared production facilities	0–12 months
Tire/rubber companies	Signal demand for bio-isoprene at target cost levels	12–24 months
Technology developers	Resolve IP constraints; partner with strain/DSP incumbents	0–18 months
Investors	Fund multipurpose C10–C15 pilot capacity	12–24 months

Peptides: Platform and Discovery

STAKEHOLDER	PRIORITY ACTION	TIMELINE
Cosmetics brands	Define peptide space and positioning: functional potential and corresponding requirements	0–12 months
Ag/food companies	Define target peptides for preservation, biocontrol	0–18 months
Technology developers	Build kg-scale production platform for any peptide	0–18 months
Investors	Fund shared discovery/screening infrastructure	0–24 months
Coalition	Create shared peptide library; coordinate discovery priorities	0–18 months

Non-Catalytic Proteins: Functional Performance

STAKEHOLDER	PRIORITY ACTION	TIMELINE
Cosmetic brands	Define the protein space and positioning potential for functional and biologically active molecules	0–24 months
Infant formula majors	Qualify precision-fermented lactoferrin, α-lactalbumin	0–24 months
Sports nutrition brands	Commit to PF whey protein volumes	0–18 months
Food/beverage CPGs	Test functional proteins (foaming, gelling, emulsification)	12–36 months
Investors	Fund scale-up of validated protein platforms	12–36 months
Coalition	Standardize functionality testing protocols	0–18 months

Hydroxy Acids: Brownfield Integration

STAKEHOLDER	PRIORITY ACTION	TIMELINE
CPGs	Commit to bio-SAP volumes for diapers/absorbents	0–18 months
Chemical platform operators	Identify brownfield sites for 3-HP bolt-on	12–24 months
Feedstock suppliers	Secure long-term, low-cost sugar supply agreements	0–12 months
Investors	Fund demonstration plants with take-or-pay offtake	12–36 months
Coalition	Convene demand aggregation across CPG buyers	0–12 months

Action-to-Molecule Heatmap

Which actions unlock scale for which molecules?

ACTION	TERPENES	PEPTIDES	PROTEINS	HYDROXY ACIDS
Demand aggregation	■ ■	■ ■	■ ■	■ ■ ■
Offtake commitments	■ ■ ■	■ ■	■ ■ ■	■ ■ ■
Brownfield integration	■	—	—	■ ■ ■
Multipurpose facility build	■ ■ ■	■ ■ ■	■ ■ ■	—
DSP optimization	■ ■ ■	■ ■ ■	■ ■	■ ■
Shared discovery/ screening	■ ■	■ ■ ■	■ ■ ■	—
Regulatory streamlining	■ ■	■ ■ ■	■ ■ ■	■
IP pooling/licensing	■ ■ ■	■ ■	■ ■	■
Standards development	■ ■	■ ■	■ ■ ■	■ ■

■ ■ ■ = Critical enabler ■ ■ = Important ■ = Helpful — = Not applicable

7. THE WORLD THESE MOLECULES BUILD

This report has been deliberately specific: which molecules, which markets, which infrastructure, which actions. That specificity is the point. But the individual molecule roadmaps, taken together, describe something larger than four separate opportunities. They describe a structural transition in how the world makes things.

The four molecule families in this report were selected because they are actionable now. They are also foundational.

The infrastructure built for terpenes creates capabilities that transfer to terpenoid pharmaceuticals. The fermentation capacity built for 3-HP produces acrylic acid today and adipic acid tomorrow. The protein platforms validated for infant nutrition extend to biomaterials, food systems, and industrial applications that do not yet have names. Each investment opens a door to the next.

What follows is not a series of predictions. It is a picture of what becomes possible if the commitments described in this report are made.

By 2031:
First commercial wins prove the model.

Specialty terpenes and cosmetics peptides generate more than $100 million in combined revenue and demonstrate that bio-based production commands market acceptance at premium price points. The first brownfield 3-HP plants are operating with CPG offtake agreements underwriting the capital. Shared application labs are compressing qualification timelines that once stretched to three years. Workforce retraining programs are scaling alongside production, with operators reporting that a substantial share of biomanufacturing roles can be filled through community college training or industry retraining, drawing from legacy manufacturing and energy workforces.

This is the high-value, low-volume phase: products that prove the technology, fund the platform, and build the credibility that unlocks the next round of capital.

By 2036:
Platform economics take hold.

The first commercial-scale isoprene plant is running. Multipurpose fermentation hubs are emerging in the US Midwest, leveraging agricultural feedstock infrastructure, and along EU chemical corridors through brownfield integration. Bio-based acrylic acid is approaching cost parity with petrochemical routes. China's state-backed biomanufacturing network, already the largest coordinated scale-up effort in the world, is maturing in parallel, intensifying both competitive pressure and the urgency of Western coordination.

The industry structure is shifting. Vertical integration gives way to a specialized horizontal stack: design, strain engineering, fermentation, downstream processing, formulation, and application. Standardized multi-tenant facilities enable project finance structures that were impossible when every plant was bespoke. AI is compressing R&D cycles from years to months, and the compounding learning effects across molecule families are driving costs down faster than any single program could achieve alone. Bio-acid revenue crosses $1 billion across multiple partners.

By 2041:
Biology becomes the default.

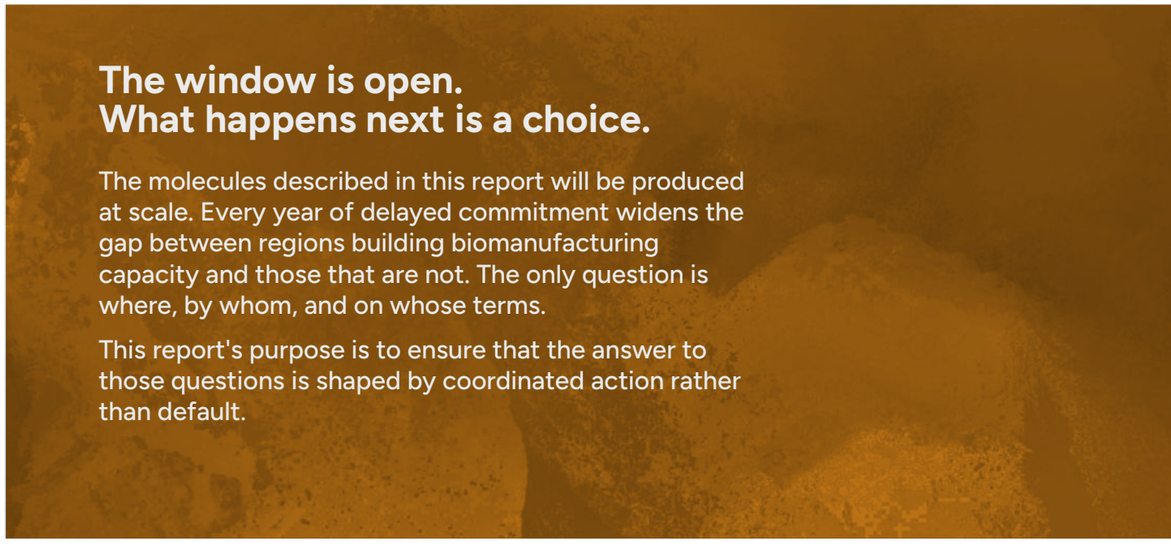
The transition is no longer about replacing petrochemical incumbents molecule by molecule. Biology is the default route for new product development in personal care, food ingredients, and specialty chemicals, not because of sustainability mandates but because bio-based routes deliver superior performance, greater supply chain resilience, and competitive economics.

Regional biomanufacturing hubs employ tens of thousands, many retrained from fossil fuel and legacy manufacturing sectors. Facilities replicate rather than scale up: modular, standardized designs deploy like infrastructure. Fermentation capacity reaches ten to twenty times current levels. The $700 billion to $1.1 trillion market opportunity mapped in Report 1 comes into view.

By 2046:
Distributed production reshapes industrial geography.

Production facilities are as standardized as logistics warehouses. Next-generation feedstocks, including waste carbon and municipal waste streams, are mainstream inputs. The four molecule families in this report are mature platforms—each having followed compressed versions of the lysine cost trajectory from specialty pricing to commodity scale.

The industry structure resembles what computing looks like today: specialized, layered, globally distributed, and locally manufactured. Design happens everywhere. Production happens where feedstock, energy, and talent converge. The countries and companies that built capacity in the 2020s and 2030s hold structural advantages that late entrants cannot easily replicate.



The window is open. What happens next is a choice.

The molecules described in this report will be produced at scale. Every year of delayed commitment widens the gap between regions building biomanufacturing capacity and those that are not. The only question is where, by whom, and on whose terms.

This report's purpose is to ensure that the answer to those questions is shaped by coordinated action rather than default.

8. DEFINITIONS, METHODOLOGY & APPENDIX

Key Definitions

Brownfield deployment is the integration of bio-based production into existing industrial infrastructure: repurposing fermentation capacity, leveraging established chemical processing facilities, or retrofitting facilities originally designed for other purposes. Brownfield approaches can reduce capital requirements and time-to-market but constrain process design to what existing facilities can accommodate.

Greenfield deployment is the construction of new, purpose-designed facilities for bio-based production. Greenfield approaches allow optimized process design but require larger capital commitments and longer development timelines.

Hybrid routes are production pathways that combine biological and chemical conversion steps, such as fermentation to produce an intermediate followed by chemical conversion to the final product. Hybrid routes can improve yields, reduce costs, or enable the production of molecules that pure biological routes cannot efficiently produce.

Downstream processing (DSP) is the set of unit operations required to recover and purify the product from fermentation or cell culture broth into a form suitable for its intended use, including cell separation, disruption (if needed), extraction, purification, concentration, and often formulation. DSP frequently accounts for a major share of manufacturing costs, typically 30–50% or more for high-value biologics, and is a key driver of capital requirements due to chromatography, buffer, and utility-intensive equipment.

FOAK/SOAK are first-of-a-kind and second-of-a-kind commercial facilities. FOAK plants carry disproportionate technical and commercial risk. SOAK plants benefit from learning but still face scale-up uncertainty. Both typically require blended financing structures.

Offtake agreements are contractual commitments by a buyer to purchase specified volumes of a product at specified prices, typically "take-or-pay" structures that guarantee revenue regardless of the buyer's actual consumption. Binding offtake agreements de-risk capital investment by providing revenue certainty.

PFAS (per- and polyfluoroalkyl substances), or "forever chemicals," are a large class of synthetic chemicals used widely in industrial and consumer products for their resistance to heat, water, and oil. They are called "forever chemicals" because they do not break down naturally in the environment or the human body. Multiple jurisdictions are moving toward strict limits or bans on intentionally added PFAS in cosmetics and other sectors due to concerns about their persistence and potential health impacts.

Platform logic is the principle that investing in one molecule within a family creates capabilities—strains, processes, and DSP configurations—that transfer to adjacent molecules, reducing costs and time for subsequent products.

Prioritization Methodology

Process Overview

Molecule prioritization followed a six-stage process:

1. **Define molecule taxonomy**: Group 300+ individual molecules into approximately 40 molecule groups based on chemical class, surfacing manufacturing synergies and market adjacencies.
2. **Quantitative screening**: Apply market and economic thresholds to identify molecule groups with sufficient scale to justify investment.
3. **Qualitative assessment**: Evaluate performance advantages, corporate interest, technological readiness, and path to cost competitiveness through expert interviews.
4. **Deep-dive analysis**: Conduct a detailed assessment of shortlisted molecule groups.
5. **Coalition alignment**: Validate prioritization with coalition members through working sessions and steering committee review.
6. **Workshop validation**: Pressure-test conclusions with broader expert group. Confirm "why now," critical enablers, and dependencies.

Selection Criteria

Quantitative Thresholds

- Total market size in 2030: >$1.5 billion
- Biotech addressable market potential in 2030: >$1 billion
- Unit price: generally >$3/kg to exclude ultra-low-value commodities where biotech's cost premium would preclude profitability. High-volume molecules like hydroxy acids can qualify on scale economics even where unit price falls below this threshold.

Qualitative Factors

- Performance advantage or drop-in compatibility
- Corporate interest and consumer pull
- Biotech cost competitiveness potential
- Technological readiness and scaling potential

Expert Interviews

More than 30 expert interviews were conducted between October and December 2025, spanning:

- Technology developers and biotech executives
- CPG and chemical company R&D and procurement leaders
- Investors and venture capital partners
- Academic and government research leaders
- Former executives from companies including Amyris, ADM, Novonesis, and Ginkgo

Interviews followed a structured protocol covering most promising molecule groups, key challenges to scale, unlocks and enabling conditions, lessons from past successes and failures, and recommendations for coalition action.

Workshop Validation

A full-day workshop was held on November 25, 2025, at L'Oréal's premises in Saint-Ouen, France. Participants included coalition members and invited experts. The workshop validated the four priority molecule groups, pressure-tested technical and commercial assumptions, and developed initial action plans for each molecule family.

Data Sources and Analytical Frameworks

Market data: Market sizing draws on publicly available industry reports, company disclosures, and proprietary McKinsey analysis. Market projections assume continued technological development, adequate investment, and no regulatory bans on advanced biotechnologies.

Cost analysis: Production cost estimates use a cleansheet (bottom-up) modeling based on representative technical specifications for capital expenditure, labor, energy, feedstock, and materials. Cost-reduction potential is estimated by applying improvement factors derived from expert assessment of technology and operational levers.

Sustainability metrics: Where referenced, sustainability estimates draw on lifecycle assessment methodologies, academic publications, and industry benchmarks. Full lifecycle analysis for specific molecules and production routes was beyond the scope of this report.

What We Did Not Prioritize

Ten molecule groups were shortlisted for evaluation. Four were selected as priorities for this report. The remaining six, dicarboxylic acids, amino acids, specialty fatty acids, enzymatic proteins, macrolides, and microbial products, were not prioritized for the following reasons:

Dicarboxylic acids (adipic, succinic, itaconic): Strong drop-in potential for nylon and polymer applications, but bio-succinic first wave faced quality and cost challenges. Current bio routes yield below 100 g/L and incur high downstream costs per kilogram. Intense price competition with mature petrochemical production at a large scale. May merit reconsideration as strain engineering and process optimization improve economics.

Amino acids (lysine, glutamic, specialty AAs): Established bio routes with large incumbents (lysine at 3.6 million metric tons globally[50]). The near-term pipeline for commodity amino acids is unclear, given intense price competition. Fermentation-derived amino acids are typically used in low-value animal feed applications. Specialty amino acids may present niche opportunities but lack the combined demand to justify coalition focus.

Specialty fatty acids (EPA, DHA, tailored oils): Algal EPA/DHA commercialized. Yarrowia and microalgae are producing tailored oils with progress in solvent-free recovery. Custom chain length and functionalization offer opportunities, but cost-optimization challenges in oxygen-heavy fermentation and flavor/odor control in consumer products limits near-term scale potential.

Enzymatic proteins (industrial enzymes): Mature market with established players (Novonesis, IFF, AB Enzymes). Platform consolidation is ongoing. Growth potential in recycling (PET hydrolases) and specialty applications, but market structure favors incumbents over new entrants. Not a priority for coalition coordination given existing commercial maturity.

Macrolides/macrocyclic lactones: Niche applications in agriculture and pharma. Complex biosynthetic pathways. Low titer challenges. The market size does not meet the quantitative thresholds for coalition prioritization.

Microbial products (probiotics, biostimulants, biocontrol): Strong commercial activity in cosmetics, food, and feed with established players. Regulatory pathways exist (EPA biopesticides, EU biostimulants). Scale-up investment concentrated in Asia. The market is growing, but coordination needs differ from molecule-focused prioritization.

Important note: Exclusion from this report's priority list does not indicate commercial unattractiveness. These molecule groups may represent significant opportunities for individual companies, and some figures in current market assessments do not yet capture full application potential.

The prioritization reflects AB4S's assessment of where coalition-level coordination can effectively accelerate deployment in the near term, not a judgment on the long-term viability of excluded categories. Future reports may revisit these molecules as market conditions, technology readiness, and coalition capabilities evolve.

[50] Lysine market size, share, growth, and industry analysis, by type (Lysine Chloride, Lysine Sulphate), by application (Animal Feed, Food Industry,Healthcare), regional insights and forecast to 2033. Market Reports. December 2025. https://www.marketreportsworld.com/market-reports/lysine-market-14716821

7. THE WORLD THESE MOLECULES BUILD

The AB4S Coalition

Advanced Biotech for Sustainability (AB4S) is an industry-led coalition of companies across the value chain—including consumer goods, specialty chemicals, biotechnology, and investment—positioned as an industry steering group and facilitator, not an inventor. The technical innovations exist. The challenge is coordination: aligning fragmented demand, connecting stakeholders across the value chain, de-risking capital deployment, and accelerating qualification cycles.

The coalition's ambition is to make it easier for individual actors to commit by reducing the coordination costs that have historically stalled industrial biotechnology. Each binding offtake agreement, each shared facility, and each standardized protocol increases the likelihood of the next commitment. The molecules are known. The market signals are clear. What remains is collective and coordinated execution on the most relevant targets.