HEMI-COAT

Conversion of hemicellulose to coatings

36th CORNET call

D1.6
HemiCoat market analysis and exploitation strategy

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This deliverable has been prepared in the context of the funded project HemiCoat in the framework of the Collective Research Networking (Cornet) supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK, funding code 01IF00399C) through the AiF (German Federation of Industrial Research Associations e.V.) based on a decision taken by the German Bundestag and by the Walloon region as funding with the n° 2310168 (Convention number).

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Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Description
A. terreus	*Aspergillus terreus*
bn	billion
C. glutamicum	*Corynebacterium glutamicum*
CAGR	compound annual growth rate
CapEx	Capital Expenditures
FCM	Food Contact Materials
GMM(s)	genetically modified microorganism(s)
HC	hemicellulose
IA	Itaconic acid
k	kilo
LCA	Life Cycle Assessment
m	million
M&A	Mergers & Acquisitions
MDF	Medium-density fibreboard
MMA	methyl methacrylate
OpEx	Operating Expenses
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SME(s)	Small and Medium-sized Enterprise(s)
SSbD	European Commission’s Safe and Sustainable by Design
STPP	sodium tripolyphosphate
USD	United States dollar
VOC	volatile organic compounds

1. Executive summary

HemiCoat evaluates the valorization of hemicellulose (HC) by-products from woody biomass into higher-value bio-based materials. The project's main pathway converts HC-derived pentoses into itaconic acid (IA), which can then be chemically modified into bio-based surfactants and coatings. A parallel route uses HC-derived oligomers for bio-based wood adhesive formulations. The market analysis therefore, focuses on IA as the central intermediate product, while also assessing IA-based coatings and surfactants, HC-derived adhesives, and alternative HC sugar valorization routes such as furfural.

The overall conclusion of the study is that IA is a strategically relevant bio-based platform chemical. Still, its commercial opportunity is currently strongest in value-added, specification-driven applications rather than in broad commodity markets. IA has a wide range of technical applications because it can serve as a reactive building block for polymers, resins, latex binders, dispersants, surfactants, coatings, adhesives, detergent ingredients, personal care products, and other specialty materials. However, the market is still relatively small and has grown more moderately than expected. The global IA market is estimated at approximately USD 110 million in 2024, with production concentrated in the Asia- Pacific region, especially China.

A survey on IA and its applications was conducted within the User Committee of the project to provide an important industrial check against these wider market findings. The survey involved five companies from the German User Committee, including firms active in coatings, adhesives, and chemical production. All respondents rated investment in bio-based alternatives such as IA and IA derivatives as very likely within the next three to five years and identified coatings and adhesives as major areas of interest and assessed the market potential for IA and its derivatives as moderate to very high. This confirms one of the study's central assumptions, that there is real near-term industrial pull for bio-based alternatives in the sectors targeted by HemiCoat. At the same time, the survey also confirms the study's more cautious conclusions. Although the companies expressed strong interest, actual implementation remains low, with only one of the five respondents currently using IA in its processes. This mirrors the broader market analysis, which describes IA as promising but still not widely adopted in Europe. The gap between interest and implementation is therefore not a contradiction, but one of the main findings. The survey shows that potential customers are attentive to IA-based solutions, while the rest of the study explains why this interest has not yet translated into broad market uptake. Survey respondents identified limited supply and supply security as key concerns and a main obstacle. The wider study supports this point by showing that global IA production is concentrated in a limited number of producers and that Asia-Pacific supplies more than half of global demand. Europe has strategic interest in IA because of circular bioeconomy goals, sustainability regulation, and the demand for bio-based materials, but its own IA production and downstream ecosystem remain comparatively underdeveloped. For European users, this creates a tension between interest in local, sustainable, bio-based value chains and continued dependence on external supply. Price competitiveness is another area where the survey and the wider analysis align closely. The User Committee identified cost competitiveness and price-performance balance as important factors. The market study shows why this is critical. IA remains more expensive than established petrochemical substitutes such as acrylic acid, maleic anhydride, and fumaric acid. In Q1 2026, IA in Europe was reported at 2.2–2.6 USD/kg, compared with acrylic acid at 0.975 USD/kg, maleic anhydride at 1.23 USD/kg, and fumaric acid at 1.3–1.6 USD/kg. As a result, IA is currently positioned as a higher-priced specialty or bio-based option rather than a low-cost drop-in substitute. This supports the conclusion that HemiCoat should not attempt to compete primarily on commodity prices.

The survey also highlights regulatory compliance as an important driver and regulatory hurdles as a barrier. This dual role is consistent with the broader study. On the one hand, European regulation and policy direction create demand for safer, more sustainable, bio-based, and lower-carbon materials. This supports the case for IA derivatives in coatings, detergents, surfactants, adhesives, and related applications. On the other hand, regulated markets require qualification, standards of compliance, documentation, and proof of long-term performance. The survey's emphasis on regulatory hurdles, therefore, reinforces the report's recommendation to address regulatory and standards of pathways early rather than treating them as a late-stage commercialization issue.

A further point of comparison is the role of sustainability. The broader market study presents sustainability, renewable carbon, circular bioeconomy alignment, and reduced dependence on fossil resources as important strategic advantages for IA and HC-derived materials. The survey results are more nuanced, as the respondents were interested in bio-based alternatives, but the decisive factors were compatibility with existing infrastructure, regulatory compliance, customer demand, and cost competitiveness. Sustainability and bio-origin matter, but they are not sufficient on their own. This is an important practical conclusion for HemiCoat. The project should not rely only on the assumed environmental profile of IA-derived products, but it must also demonstrate performance, process compatibility, reliable supply, and acceptable economics. For this reason, sustainability questions are addressed through a dedicated life cycle analysis in Deliverable *D 1.5 LCA of hemicellulose oligomers and itaconic acid-based products* within HemiCoat, providing a more robust basis to assess environmental benefits and compare them with conventional alternatives. Survey and market analysis also strengthen HemiCoat's prioritization of downstream applications. The survey points to coatings and adhesives as major areas of industrial interest. The wider report identifies IA-based coatings and surfactants, detergents and hygiene-related ingredients, selected personal care applications, and bio-based adhesives as the most promising market segments. These are applications where bio-based origin, regulatory alignment, and technical performance may justify a premium. The strongest market path is therefore not the sale of IA as an undifferentiated intermediate, but the development of validated IA- and HC-derived materials for specific end uses.

Overall, the User Committee survey and the broader study are consistent. The survey confirms near-term market interest, especially in coatings and adhesives, while the wider analysis explains the structural barriers that still limit adoption, such as supply constraints, higher costs, regulatory hurdles, scale-up challenges, and the need for application-specific performance validation. Together, they point to the same exploitation strategy for HemiCoat, that is to focus on differentiated downstream products, validate them under industrial conditions, build partnerships with formulators and end users, and prepare credible cost, supply-chain, regulatory, and sustainability evidence. Demonstration projects, toll manufacturing, licensing, joint ventures, and collaboration with application laboratories are therefore more suitable routes than direct competition in high-volume commodity IA markets.

2. Introduction

HemiCoat is a two-year project in the framework of the Collective Research Networking (Cornet) supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK, funding code 01IF00399C) through the AiF (German Federation of Industrial Research Associations e.V.) and by the Walloon region, as funding with the n° 2310168 (Convention number) with a total budget of approx. 1 million euros equally shared between the national funding agencies of Germany and Wallonia (Belgium).

2.1. HemiCoat project description

The consortium of the HemiCoat project is an international collaboration consisting of DECHEMA e.V., DBFZ gGmbH in Germany, and Celabor s.r.l. and Materia Nova in the Walloon region, focusing on the valorization of hemicellulose (HC) by-products derived from woody biomass, aiming to produce high-value chemicals for use in sustainable coatings, adhesives, and functional additives.

HemiCoat's overall project objective represents the idea of utilizing all components of wood and wood-based products to maximize resource efficiency, reduce waste, and enhance the sustainability of biomass utilization. Woody biomass possesses distinctive properties that can be strategically valorized into high-value products, thereby advancing the development of a circular bioeconomy. Such an integrated approach can minimize the environmental impact, reduce dependency on fossil resources, and enhance the economic resilience and competitiveness of wood-processing industries. Despite its considerable potential, HC, being a substantial fraction of woody biomass, remains largely underutilized, with current practices predominantly focused on (low-value) energy recovery through combustion. In parallel, the coatings and adhesives sectors are encountering increasing pressure to adopt bio-based, low-carbon alternatives that address regulatory requirements and eliminate the use of hazardous compounds. By redirecting HC toward producing sustainable chemical building blocks and functional materials, this strategy presents substantial opportunities for generating additional revenue streams, improving resource efficiency, and positioning industries at the forefront of the growing global bioeconomy.

HemiCoat's main objective is to valorize HC streams by converting them into high-value chemicals for applications in coatings, adhesives, and functional additives. Starting from residual fractions from pulp production and agricultural lignocellulosic biomass, the project develops innovative methodologies to harness biobased building blocks through optimized purification, fermentation, and further chemical processing to advanced coatings and surfactants. The project's primary objectives are: (i) to maximize the recovery of HC from lignocellulosic biomass processing, and (ii) to utilize the HC-derived monomers in fermentative processes to synthesize itaconic acid (2-Methylidenebutanedioic acid, IA). Further added value is achieved through chemical IA modification, particularly the esterification of sulfonated IA with medium- and long-chain alcohols, enabling the production of bio-based surfactants and coating materials. In addition, other HC-derived compounds are being developed as biobased adhesives, and the entire project chain is assessed in an economic and sustainable context.

Figure 1 displays the overview of the HemiCoat processes and the target products and product classes of the market analysis. Herein, the HemiCoat project establishes routes aiming to maximize the usage of sugars from industrial HC-containing hydrolysates. In one pathway, monomeric pentoses derived from HC are subjected to fermentation processes to produce itaconic acid (IA), which is subsequently modified through targeted chemical transformations. In a parallel approach, HC-derived oligomers are chemically converted into sustainable wood adhesive formulations, offering bio-based alternatives to conventional fossil-derived products.

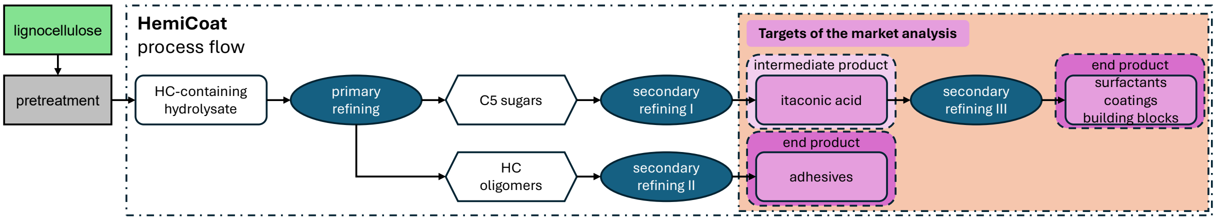

Figure 1. Overview of the HemiCoat process flows with the targets of the market analysis.
HC from differently pretreated wood hydrolysates is separated in a primary refining process to obtain a C5 sugar (pentose) fraction, mainly xylose, and HC oligomers. In secondary refining, the xylose is fermented to IA, the key intermediate product that is chemically modified in a secondary refining III to produce surfactants or coatings, the end products of the HemiCoat process flow. In a parallel process, HC oligomers, after primary refining, are transformed into adhesives in a secondary refining II, and the resulting adhesives are the second line of end products of the HemiCoat process. All products of the secondary refining steps (I to III) are the targets of this market analysis report.

The anticipated outcomes of this research are expected to directly benefit small and medium enterprises (SMEs) engaged in producing IA-based products by diversifying raw material sources, enhancing product quality, and reducing costs. The HemiCoat project holds the potential for significant technological advancements by enabling SMEs to substitute traditional fossil-based reagents with biobased alternatives derived from itaconic acid. This could extend the application range to include anhydrides, plastics, coatings, and functional additives.

2.2. Aim and structure of the market analysis report

The aim of the market analysis and economic evaluation of the processes within the Hemicoat project is to support SMEs operating in valorizing lignocellulosic and hemicellulosic agro-industrial and forestry residues, potentially catalyzing new sustainable business models within the bioeconomy sector. IA is the main intermediate product and key building block for further synthesis of coatings and surfactants. Therefore, IA is the major target of the project's economic evaluation. Following the Hemicoat process chain, IA-based esters will provide added-value products, such as the sodium *n*-octyl sulfoitaconate diester.[1] The economic assessment of this bio-based anionic surfactant type represents this market analysis's second target. Finally, the main target markets are (re)evaluated economically, and further market expansions or the prioritization of market segments are discussed. The economic competitiveness of the Hemicoat process is benchmarked against the global and local markets of central Europe, aiming to define the legitimate (maximal) expenses to compete in the respective markets. The market analysis of the (intermediate) products from Hemicoat will provide an economic evaluation for the SMEs of the user committee SME and the foundation for evaluating future research to overcome economic drawbacks and improve the utilization of existing markets.

2.3. Mapping HemiCoat's outputs

This section aims to map HemiCoat's grant agreement commitments within the formal deliverables and task descriptions against the project's respective outputs and work performed. This report is listed as Deliverable *D1.6 HemiCoat market analysis and exploitation strategy* and is due in M22 of the project, June 2026, and is assembled in *WP 1, task 1.5 Market study*. **Table 1** lists, describes, and justifies the tasks and subtasks in HemiCoat connected to the report.

Table 1. Adherence to HemiCoat's task description & Deliverables.

HemiCoat task	Description	Justification
Task 1.5 Market analysis and exploitation strategy (M1 to M22)	An in-depth market analysis to assess the current HemiCoat market situation, identify growth potential and barriers to adoption, and steer the technical work packages from the outset. It will evaluate key market criteria (e.g., prices, volumes, growth rates), map competing products and processes across multiple application sectors, and synthesize internal project findings with external data, literature, and expert input from partners and an SME User Committee to keep insights current on trends, sustainability, and technology developments.	This market analysis is essential for a European project such as HemiCoat because it ensures EU-funded R&I is market-driven and translates into real deployment, competitiveness, and SME uptake across European value chains. By identifying demand, competitors, adoption barriers, and regulatory/standards constraints early, it de-risks scale-up and aligns technical work with EU sustainability and circular-economy objectives.
Subtask 1.5.1 Market analysis of the intermediate product Itaconic acid (IA)	A market analysis of the intermediate product IA to assess the current demand, pricing, and supply dynamics, key applications, and competing substitutes, and the main barriers and opportunities for scaling adoption in target sectors.	This is important because understanding IA's market size, pricing, competition, and adoption barriers is essential to validate the project's business case and steer development toward applications with the highest commercial and impact potential.
Subtask 1.5.2 Alternatives derived from Hemicellulose sugars	Alternatives derived from Hemicellulose sugars include producing furfural as a valorization route for pentosan-rich side streams from existing biorefineries, leveraging an established and growing market with a potential European supply gap.	By valorizing hemicellulose side streams into a proven, high-demand chemical like furfural, European biorefinery can improve economics and resource efficiency while helping address Europe's supply gap.
Subtask 1.5.3 Market analysis of the final products of HemiCoat: Biobased coatings, surfactants and adhesives for wood	A market analysis of HemiCoat's final products: bio-based coatings, surfactants, and wood adhesives will assess market size/growth, pricing, target segments, and key competitors. It will also identify the main adoption barriers (e.g., standards, regulation, performance, and scale-up) to focus on commercialization efforts.	Aligning development with verified market demand and compliance requirements, this analysis reduces commercialization risk and directs HemiCoat's resources to the applications with the strongest competitive advantage and fastest adoption potential.
HemiCoat Deliverables		
D1.6 HemiCoat market analysis and exploitation strategy		

HemiCoat's market analysis provides an evidence-based view of current market conditions, growth potential, and adoption barriers, ensuring the technical work packages are steered toward the most commercially relevant targets from the outset. It assesses core market criteria, such as prices, or volumes as well as competing solutions, and sector-specific requirements using a combination of project results, external data and literature, and expert input from partners of the SME User Committee. Specific focus areas include the intermediate IA, to validate demand, pricing, substitutes, and scale-up opportunities, and hemicellulose-based alternatives such as furfural, which could valorize side streams and help address a potential European supply gap. Finally, this report evaluates HemiCoat's end products, in particular bio-based coatings, surfactants, and adhesives.

2.4. Survey on use and outlook for IA in the User Committee

A survey on IA and IA-based (end) products with companies from the User Committee in Germany was conducted. The survey was designed to capture first-hand industrial perspectives on current and anticipated demand and preferred application areas (e.g., coatings or adhesives). In addition, participants were asked to identify perceived barriers to uptake, such as availability and supply security, or price and quality. The results provide a condensed, market-driven complement to literature and database research, and help prioritize the most relevant end-product routes and validation activities for the German and, by extension, European market context. **Figure 2** presents an overview of the survey results, summarizing the responses to the questions most critical for assessing market potential and adoption conditions. It highlights the main trends observed across participants and the key criteria shaping interest in IA and IA–based products.

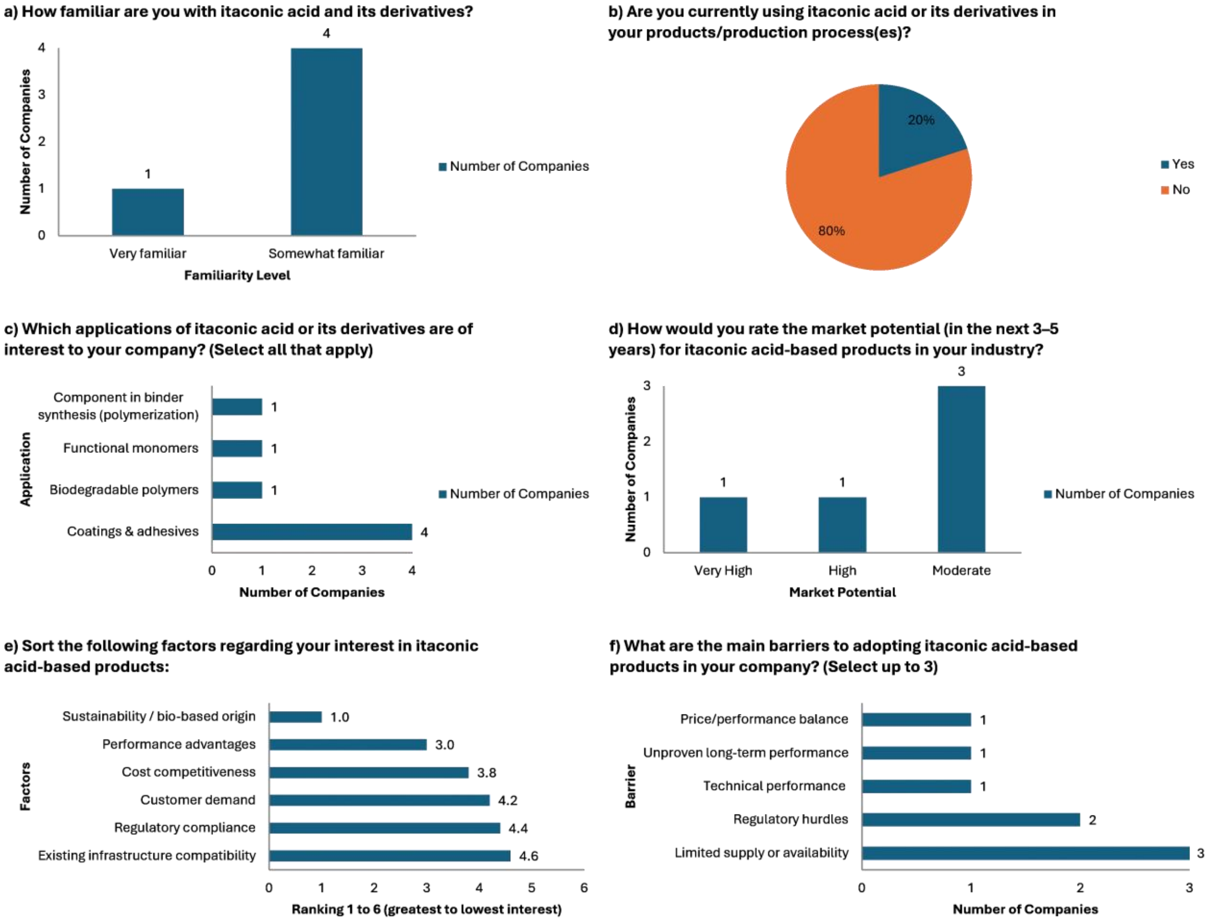

Figure 2. Key survey responses on itaconic acid and IA-based end products.
Survey respondents (n=5) were R&D staff from German User Committee companies spanning coatings/adhesives (3) and chemical production (2), including one SME (11–50 employees) and four large enterprises (>200 employees). All rated investment in bio-based alternatives, such as IA (derivatives), as very likely within 3–5 years. Panels (a–f) present the survey's key questions and summarize the corresponding responses.

Overall, the survey responses indicate significant near-term industry pull for IA and IA–based products among the German User Committee companies. Herein, respondents largely expect a high likelihood of investment in bio-based alternatives over the next 3 to 5 years, with the major interest in applications in coating and adhesives. The survey indicates that User Committee companies perceive the market potential for IA and its derivatives as moderate to very high, but implementation remains low, with only 1 out of 5 companies currently using it in their processes. Interest is driven primarily by compatibility with existing infrastructure, regulatory compliance, customer demand, and cost competitiveness, while performance improvements and sustainability/bio-origin are less decisive factors. The main barriers identified are limited supply/availability and regulatory hurdles, with secondary concerns around price–performance balance, unproven long-term performance, and technical performance.

Based on this, HemiCoat and other IA-focused projects should focus on drop-in compatibility with existing infrastructure, an early regulatory/standards pathway, and a robust cost and supply-chain validation, supported by application-relevant data on long-term and technical performance to reduce adoption risk.

3. Material and Methodology

This market research report is based on research and analysis being performed from Q4 2024 to Q2 2026. Secondary market data supported by artificial intelligence (AI) were used to assess the current market situation and estimate the market's development for the key (intermediate) products of the Hemicoat process flow, namely itaconic acid, itaconic acid-based anionic surfactants, and methyl methacrylate (MMA). Data was collected through the following references and tools:

- Research articles and reviews
- Patents
- Public databases for a broader overview of the chemical classes
- Market studies and other economic analyses
- Large Language Model tools

AI's workflow to research and organize the data included the following general steps:

1) Set up a structured analysis framework
2) Plan targeted queries to identify relevant information, in particular companies and products

The output generated with AI support was rephrased and manually double-checked to ensure accuracy, consistency, and alignment with the underlying sources.

In addition to product-specific data being accessible for IA and MMA, secondary data on higher-level product groups that contain other similar products in addition to the target product(s) had to be applied for itaconic acid-based anionic surfactants. Herein, anionic surfactants in general were considered as the product group of interest. The data sets in both cases allow price and market estimates and provide market and trading parameters, such as import and export. The information from secondary sources covers the following aspects:

- Technical information
- Current global market volumes and market shares of chemicals or chemical groups
- Past and future market growth of chemicals or chemical groups
- Data on key producers, suppliers, and fabricants
- Trends and market developments
- Price trends of feedstocks for the IA fermentation

4. Intermediate product of HemiCoat: Itaconic acid

4.1. Production and applications

Itaconic acid (IA), also known as methylene succinic acid (CAS 97-65-4), is a C5-dicarboxylic acid with an α,β-unsaturated methylene group at the C2 position, making it highly reactive and versatile for chemical modifications. The condensed structural formula of IA is displayed in **Figure 3**.

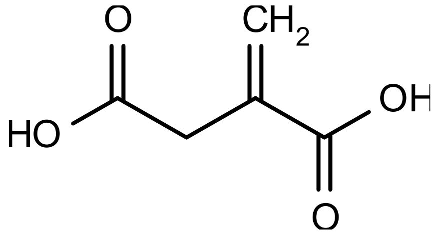

Figure 3. Itaconic acid (IA), a C5-dicarboxylic acid with an α,β-unsaturated methylene group at C2.

These properties enable IA to serve as a precursor for numerous biopolymers and other industrially relevant compounds, placing it among the U.S. Department of Energy's top 12 platform chemicals.[2,3] Although chemical synthesis of IA is technically feasible, it is not economically viable. Instead, biological production through fermentation is the preferred method. In the early 1930s, a filamentous fungus was recognized as being able to produce itaconic acid and was consequently described as *Aspergillus itaconicus*.[4] At the end of the same decade, a fermentation process using *Aspergillus terreus* (*A. terreus*) – the major production strain of today – was introduced.[5] In 1945, more efficient *A. terreus* strains were isolated and applied in submerged and surface cultures.[6,7] Nowadays, the most established industrial process still utilizes *A. terreus* to ferment glucose,[8] molasses,[9] or starch-based substrates[10]. More recently, alternative metabolically engineered microbial hosts have been explored,[11] including strains of *Yarrowia lipolytica,*[12,13] *Ustilago sp.,*[14–16] and *Escherichia coli,*[17] though these generally yield lower IA titers[18,19] compared to *A. terreus* fermentations. Therefore, although *A. terreus* is the microorganism of choice for today's production of IA, efforts are still ongoing to improve IA yields through ongoing strategies integrating metabolic[20,21] and bioprocess engineering.[22]

Global production of IA is dominated by fermentation, which is primarily executed through *A. terreus*-based submerged cultures. It has been industrially scaled since the 1960s and remains the economic and technical standard due to its high yields and process robustness.[18,23] The fermentation route relies on carbohydrate-rich feedstocks:

- Glucose from starch hydrolysates is the preferred industrial substrate due to its high conversion yield (0.5 to 0.6 g IA/g glucose) and compatibility with *A. terreus*.[3,24]
- C5 sugars, such as xylose or arabinose, derived from lignocellulosic biomass and processed at lower yields (~0.5 g IA/g xylose, ~0.4 g IA/g arabinose) in lab-scale fermentation.[25,26]

Additionally, there are strategies to utilize molasses or hydrolysates, e.g., from wheat straw or cellulose pulp, as feedstocks,[27–29] as there is increasing interest in utilizing 2nd generation feedstocks, e.g., lignocellulosic biomass from agricultural residues and woody materials, as potentially cost-effective and renewable substrates.[29–33]

IA, a bio-based, top value-added chemical[2] has attracted considerable attention across various industries due to its unique chemical properties and alignment with the goals of sustainability, biodegradability, and enhanced performance.[34] One of its principal functions is that it serves as a valuable monomer in the synthesis of superabsorbent[35,36] and specialty polymers[37,38] used in biodegradable plastics,[39] resins,[40–42] and coatings,[43,44] offering environmentally friendly alternatives to petrochemically produced products in paints and adhesives. By blending with other compounds, IA can play a crucial role by enabling the creation of materials, such as "plastics" that more readily decompose in the environment, thereby addressing the global demand for sustainable alternatives to petroleum-based products.[37,45]

IA derivatives function effectively as cleaning, beauty, and hygiene articles in the household,[46] or in the pharmaceutical sector,[47–49] where IA and its derivatives align with the rising preference for natural, bio-based ingredients.[50] The agricultural sector benefits from IA's biobased properties through its application in herbicides[51] and as a fertilizer additive[52] to improve nutrient delivery. Further applications for IA (derivatives, such as Itaconic anhydrate) may be explored in emerging fields, such as battery electrodes,[53] or in flame retardant compounds,[54] where its biobased origin aligns with the growing demand for sustainable and high-performance alternatives to petrochemically based materials. The broad applicability of IA and its derivatives across these diverse sectors underscores its importance in the ongoing shift toward sustainable, bio-based industry solutions.

Thus, several chemical and biotech companies are engaged in the production of itaconic acid and its derivatives. These firms utilize various manufacturing processes to produce a range of itaconic acid-based products. This industrial activity forms the basis for estimating global production capacity and market availability. The following section provides an overview of leading global producers and the range of IA products available in the (US) market.

4.2. Producers and IA-based products

The global production landscape of IA is shaped by a limited group of manufacturers. This chapter outlines the major producers, offering insights into the competitive environment and commercialization strategies for IA on a global scale. An overview of enterprises for the global production, trading, and utilization of IA with a focus on Europe is listed in **Table 2**.

Table 2. Overview of the key global producer, distributor, and fabricator of IA.[55–58]

Region	Company	Business model
Asia (China)	Zhejiang Guoguang Biochemistry	Industrial fermentation of IA. One of China's major producers.
	Qingdao Kehai Biochemistry	Produces and exports IA globally, with large-scale fermentation capacity.
	Jinan Huaming Biochemistry	Fermentation-based production for global supply chains.
Europe/US	Itaconix PLC/Corporation	Specializes in converting IA into biodegradable specialty polymers for detergents, personal care, and industrial uses. Official legal headquarters and incorporated entity is Itaconix PLC, based in London, UK, substantial U.S. presence and generates most of its revenue operating as Itaconix Corporation, headquartered in Stratham, New Hampshire
Europe/Global	Merck KGaA	Specialty chemicals and life science applications; listed among prime IA contributors.
Europe	BASF SE	Sustainable IA production R&D and bio-material integration.
	DSM N.V.	Dutch company leveraging bio-based materials, including IA.
	Corbion N.V.	Dutch biotech firm with fermentation platforms producing organic acids including IA.
	Novonesis	Enzyme & fermentation biotech—produces natural IA
	Synthomer PLC	Mid-cap UK specialty chemicals firm, advances sustainable polymer innovation by integrating bio-based IA into products, supporting SME-driven solutions through scale-up, market access, and local value chain development
	Lucite International	Fermentation-based IA for bio-acrylics in the UK

Among the global producers utilizing IA, one company – Itaconix Corporation – distinguishes itself by relying exclusively on IA derivatives for its entire portfolio of end-user products, which is an approach that sets it apart in terms of vertical integration and market positioning. According to the 2023 Itaconix Annual Report, their "*growing customer base increased the revenues to $7.9m in 2023 from $5.6m in 2022* [with the] *potential as an ingredient to displace acrylic acid or styrene across $20B of possible applications ranging from cleaning and hygiene to paints and composites*".[46] An overview of IA-based high-performance products by the US market leader Itaconix Corporation, is listed **Table** 3.

Table 3. Overview of the IA-based products portfolio of Itaconix Corporation (Q4 2024).[46]

Field	Product	Application
Clearing	Itaconix® DSP 2K®	Agricultural water conditioning, homecare for fabric detergents and surface cleaners, institutional and industrial detergents, oilfield water conditioning
	Itaconix® TSI® 422	Industrial cleaners, automatic dishwashing detergents, automatic dishwashing detergents, hard surface cleaners, water treatment, bathroom cleaners, laundry additives, laundry powder, tablets and pods
	Itaconix® TSI® 322	Automatic dishwashing detergents, hard surface cleaners, industrial cleaners, water treatment
	Itaconix® ONZ™ 075	Home & institutional detergents, laundry powder
	Itaconix® ONZ™ 100	Air refresher, cleaners, liquid laundry detergents, pet care, urine odor controls, wastewater & sewage treatment
	Itaconix® ONZ™ 105	Air refresher, cleaners, laundry additives, pet care, urine odor controls, wastewater & sewage treatment
	Itaconix® ONZ™ 400	Air refresher, cleaners, liquid laundry detergents, pet care, urine odor controls, wastewater & sewage treatment
	Itaconix® ONZ™ 405	Air refresher, cleaners, liquid laundry detergents, pet care, urine odor controls, wastewater & sewage treatment
	Itaconix® SF 505	Baby care, facial cleansers, formulations at extreme pH: hair relaxers, straighteners & perms, leave-on and rinse-off conditioners, liquid hand soaps, moisturizing body wash, moisturizing skin care, shampoos, sun care
Beauty	VELASOFT® NE 100	Aerosol, mousse, styling gels
Hygiene	VELAFRESH® ZP20	Deodorant, haircare, skincare
	VELAFRESH® ZP30	Deodorant, haircare, skincare
	VELAFRESH® ZP75	Anhydrous deodorant, body and foot powder, dry shampoo
	VELAFRESH® ZP95	Anhydrous deodorant, body and foot powder, dry shampoo

Following the example of Itaconix Corporation, a closer look at global pricing and market trends provides a broader view of the commercial environment of IA.

4.3. Global prices and markets

The data presented in this market analysis are based on available sources from which the information was extracted. As there is no centralized or fully reliable database, thus, the data presented in the following chapter should be considered estimations and interpreted with caution. For data, in particular, related to price and predicted market growth, multiple sources were consulted where available. In cases where more than one reference was identified, the average value was calculated for a representative estimate and is reported in this chapter to ensure a balanced and consistent presentation of market trends.

The global IA market size was valued at approximately USD 90.9 million (m) in 2023 (calculated from 4 references, USD 75.1 m to 104.9 m), or USD 108.5 m in 2024 (calculated from 4 references, USD 98.8 m to 117.8 m)[59]. **Figure 4** presents the historical market value trends alongside the compound annual growth rate (CAGR) observed over the past decade.

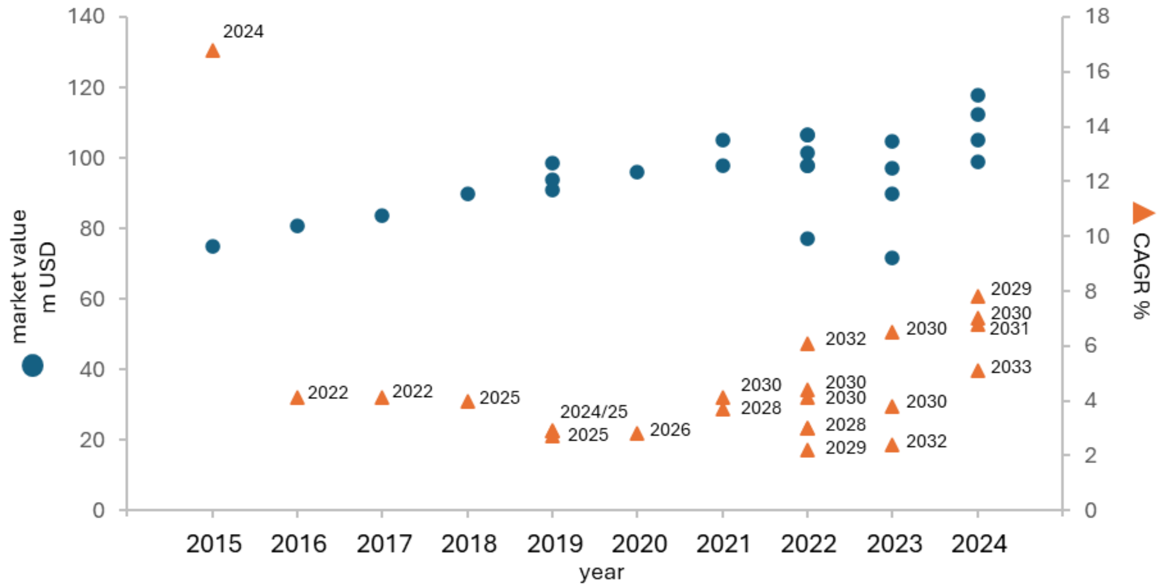

Figure 4. Market value and CAGR of itaconic acid from 2015 to 2024.
The end of the CAGR period is labeled next to the orange triangle, e.g., in 2015, the IA market size was expected to grow at over 16.8% CAGR until 2024.[60]

Between 2015 and 2024, the IA market exhibited a CAGR of over 4.2% (calculated from the market values in **Figure 4**). The 2024 CAGR of 6.7% (calculated from 4 references, 5.1% to 7.8%) reflects a renewed sense of optimism and momentum in the sector. However, this moderate growth contrasts sharply with the ambitious projections made in the early 2010s. In 2011, the IA market was valued at approximately USD 74.5 m, with expectations to reach USD 567.4 m by 2020, implying a projected CAGR of 22.3%.[61] These early forecasts ultimately proved to be overly optimistic, as market expansion did not meet initial expectations.

While there is a global consensus on the moderate growth of the IA market, production remains concentrated in specific geographical hotspots. Accounting for the highest share globally, the Asia-Pacific region leads in both the manufacturing and use of IA, supplying more than 50% of the global demand. Herein, the Chinese IA market is projected to reach a valuation of USD 21 m by 2025. Compared to that, the German market, the largest market in the EU, reached a volume of around USD 3.9 m in 2020, highlighting its relatively modest scale.[62]

While the Asia-Pacific region leads the production capacity with facilities optimized for cost-efficient production, central Europe has a growing role due to regulatory incentives for sustainable chemical manufacturing. The European IA market has seen strong growth, driven by key players investing in R&D and advanced technologies to optimize fermentation processes. These innovations have boosted production efficiency and reduced environmental impact, aligning with the region's push for sustainable chemical solutions. A major focus has been the expansion of IA applications, particularly in bio-based polymers, resins, and coatings. These materials are gaining traction across industries such as automotive, construction, and packaging due to an increasing demand for eco-friendly alternatives. Strategic collaborations with academic and research institutions have further accelerated innovation, particularly in biodegradable plastics and pharmaceuticals. These efforts have led to new product developments and strengthened Europe's position in the global IA market.[55]

Over the past decades, global IA prices have shown a consistent downward trend due to increased biotechnological production potential. In 2011, the IA price ranged from USD 1,800 to USD 2,000 per metric ton and decreased to USD 1,700 in 2018.[61,63] As of Q1 2025, the price of bio-based IA in the Asia-Pacific region ranges between USD 1,200 and 1,400 per metric ton, with China reporting spot prices around USD 1,260,[64] depending on the supplier and product quality. In contrast, European production commands a significant premium, with prices approximately 50% higher, reaching USD 1,945 in Germany or USD 2,130 per metric ton in Belgium.[64] Compared to petrochemical-based alternatives, the market price for IA remains significantly higher. For example, acrylic acid, a key petrochemical alternative, is priced around USD 1,000 per metric ton in China,[65] while maleic anhydride averages approximately USD 850 per metric ton.[66] Due to the relatively high production costs of IA, its commercial use is currently limited to specialized applications, where premium pricing is justified. These include markets where bio-based content offers a distinct value proposition, such as environmentally certified materials, sustainable packaging, or consumer goods where green branding commands a price premium.

4.4. Key price-determining parameters

Key price-determining parameters are outlined in a global and European context, influencing the production cost and market price of IA.

4.4.1. Material features and quality

The chemical characteristics of IA with two carboxyl groups and one double bond underpins its utility in producing high-performance polymers. However, achieving polymer-grade quality standards, which are needed for its end-use applications, requires downstream purification, adding significantly to production costs as purification and recovery can account for roughly 30–40% of the final cost.[67,68] Importantly, product specifications, e.g. purity, color, and inhibitory impurities, affect manufacturing steps and pricing.

4.4.2. Resource prices (feedstocks)

The cost of raw materials, particularly fermentable sugars, is another large contributor to IA production costs. Industrial itaconic acid is typically fermented from carbohydrate sources, in particular from glucose (derived from corn starch, etc.) or molasses. In a process study from 2019 the cost for glucose was assumed at 580 USD/t, while cane molasses was cited at 100 USD/t, which shows the cost gap between refined and lower-cost sugar streams.[32] The same study reported that the modeled IA production cost fell from approximately. 1,600 USD/t when glucose was used to about 620 USD/t when cheaper lignocellulosic feedstocks were used. In its "coal-supplemented case", production cost was about 600 USD/t, against a cited competitive IA selling price of 1,740 USD/t and a market price of 1,800 USD/t in that study framework.[69] A separate experimental study on corn-based processing notes that commercial IA production is generally based on corn starch converted into glucose-rich syrup, and that cost reduction is a central goal. Herein, IA production cost would need to fall to at least 500 USD/t to be economically competitive with petrochemical alternatives.[70]

4.4.3. Research and development (R&D) investments

Continuous R&D is crucial to improving fermentation yields, titer, and productivity of itaconic acid, thereby lowering unit costs. Insufficient production technology and suboptimal microbial strains have historically limited IA's cost-competitiveness.[71] Investments in strain engineering, metabolic pathway optimization, and process innovation can yield higher conversion efficiencies and by-product reductions, directly reducing operating costs. One analysis on the production of IA from woody biomass showed that a 20% increase in fermentation yield or a 20% cut in operating costs (OPEX), e.g., through R&D, could turn an otherwise unprofitable IA process profitable.[72] In addition to process intensification, strategies such as metabolic engineering of *A. terreus*, utilization of alternative microbial hosts, or the development of integrated bioprocesses can enhance IA production, thereby positively influencing the economic viability of the production process. Crucially, public and private R&D funding, particularly within the EU, plays a significant role in advancing technological innovation and facilitating the scale-up of production capacity.

4.4.4. Process design and scale-up challenges

The engineering design of IA production, spanning from fermentation technology to downstream processing, significantly influences the overall economic structure of the production process. Conventional IA production typically employs (fed)batch fermentation methods using *A. terreus* strains. However, scaling these processes to industrial volumes can present substantial challenges, including difficulties in fungal morphology control, limitations in oxygen supply into liquids, and elevated risks of microbial contamination. The primary cost drivers in IA production processes encompass both the fermentation stage, including bioreactor equipment and related utilities, and downstream purification procedures. Both stages may demand significant capital investment and high energy consumption. For example, techno-economic analyses have demonstrated that fermentation and preliminary treatment equipment constitute a substantial portion of capital expenses, and that downstream processes such as precipitation, adsorption, or extraction can represent smaller, yet significant operating expenses. The transition of IA production from laboratory-scale to industrial-scale can uncover issues related to maintaining consistent yields and productivity, whilst suboptimal scale-up strategies can diminish anticipated economic benefits. Consequently, process innovations, e.g. continuous fermentation approaches, *in-situ* product recovery techniques, or overall process intensification, are critical areas of research and development. Yet, implementing these innovations at a commercial scale poses significant technical and economic barriers. Furthermore, current commercial IA production capacities remain relatively modest, typically in the low kilotons per annum. When compared with petrochemical manufacturing facilities, which commonly operate at significantly higher production scales, this highlights a substantial economy-of-scale gap.[32,68,72]

4.4.5. Location-related factors

Production costs for IA are sensitive to geographic location due to differences in infrastructure, input costs, and regulatory regimes. Herein, factors such as energy prices, labor costs, infrastructure availability, and government policies must be considered in different regions affecting IA production economics. For example, in the EU, compared to China, 4-to-5 times higher electricity prices[73] drive up utility costs for fermentation (cooling, aeration, etc.), and strict environmental regulations can impose additional operating costs or capital upgrades[74] (e.g., for waste treatment or emissions control). Meanwhile, regions like Asia “benefit” from lower-cost labor and operate within more permissive regulatory environments, but may face other challenges such as variable feedstock quality or environmental compliance crackdowns (as seen when Chinese authorities enforced environmental inspect, fining over 29k companies).[75,76] Logistics and supply chain reliability also play a role: producers located far from end markets incur higher cargo costs and risk supply disruptions, as port delays and shipping costs can add price pressure in importing countries. Additionally, government regulations or tariffs can negatively affect the cost balance. For instance, countries, e.g. of the EU, with policies favoring biomass-derived products or penalizing high greenhouse gas emissions improve the competitive position of bio-based products, and hence producers of bio-based compounds, such as IA.[77,78]

4.4.6. CO_2 emissions and sustainability considerations

A growing factor in the market outlook for IA can be the cost of carbon dioxide equivalent emissions and the sustainability profile relative to petrochemicals. Producing IA via fermentation offers the potential for lower net greenhouse gas emissions, since the carbon in IA originates from renewable biomass. In practice, the current carbon footprint of IA production depends on the feedstock, downstream method, energy source, and process efficiency.[28,79,69] Evaluating environmental impact requires careful consideration of the fermentation process, with significant influence from both the type of feedstock and the purification approach.[28,32] Sustainability challenges can be further addressed by integrating renewable energy and using waste-derived feedstocks. With carbon pricing mechanisms (such as the EU Emissions Trading System[80] and various carbon taxes) increasingly putting a price on CO_2 output, the relatively higher CO_2 emissions are associated with (i) petrochemical alternatives to IA, or (ii) IA being manufactured far from its end-use location and therefore associated with a supply chain involving longer transport routes, as this logistical configuration (potentially) contributes significantly to the product’s overall life cycle emissions, primarily through elevated CO_2 emissions from cargo transport. The latter case would apply for IA, which is produced, e.g., in China with end-users in the EU.

To provide a comprehensive overview of the factors discussed in the previous chapter, **Figure 5** illustrates the interplay of the key parameters that determine the overall price.

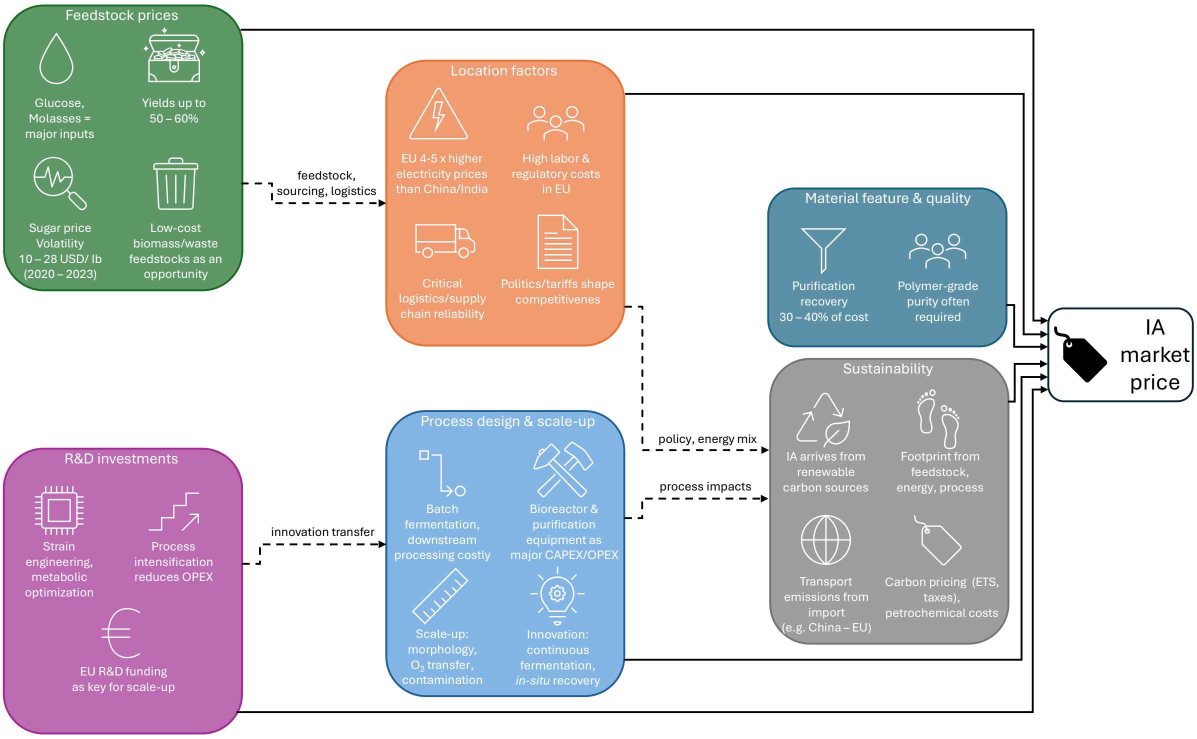

Figure 5. Overview of the key parameters that determine the market price of IA.

4.5. Central Europe market – Porter's Five Forces Analysis

Within the European Union (EU), interest in IA is motivated by strategic goals to advance the circular bioeconomy and reduced reliance on fossil-based chemicals.[81] IA is identified as one of the top renewable "building block" chemicals, and conceivably contributes to the EU bioeconomy strategies[82]. The EU market for IA, however, faces unique challenges. Production costs in Europe are elevated by factors such as high sugar/feedstock prices, expensive energy, notably electricity.[83,84] Moreover, Europe's higher labor costs[85] compared to emerging markets (e.g. in the Asia-Pacific region)[86] have directly inflated fermentation expenses, contributing to IA price quotes in Western Europe that are substantially above Asian levels. Additionally, European producers operate under stringent environmental and safety standards,[87] which, while ensuring sustainable practices, can limit operational flexibility and add compliance costs. On a positive note, European R&D initiatives (supported by European and national programs) are actively exploring new production processes, in particular genetically improved microorganisms,[88] and the production of specialty organic acids from renewable and waste feedstocks, which can cut costs at competitive yields.[89] The EU's policy environment – including carbon pricing mechanisms and sustainability incentives – could drive the critical transition to green growth[90] and hence further shape IA's competitiveness. As the EU moves toward higher carbon dioxid taxes and stricter CO_2 emission limits (e.g., Carbon Border Adjustment Mechanism),[91] bio-based products such as IA might gain a cost advantage over their petrochemical counterparts if production processes can demonstrate lower net greenhouse gas footprints. Future political decisions could encourage EU stakeholders to invest further in process innovation and supply chain optimization for IA, provided key price-determining factors are addressed.

Further details on the global market of IA are investigated in Porter's Five Forces[92] analysis focusing on the European IA monomer market dynamics.

1. Competitive Rivalry - High.

The IA market is characterized by a small number of producers worldwide, with production concentrated in China and the Asia-Pacific region.[93] Currently, price competition leads China as the dominant supplier, and only a handful of major players (several Chinese companies and a few niche Western players) compete for global customers.[59] Central Europe's market is largely supplied by these global producers, and any local producer would face the same intense competition environment. Despite the limited number of firms, rivalry is intense, as IA is a chemical commodity, and producers compete primarily on price and volume. Global production capacity covers demand, resulting in a price undercutting in the last decade and Each supplier fights to secure buyers in this niche market, keeping margins thin.[94] Moreover, companies are racing to develop new applications (e.g., IA-based latex, resins, superabsorbents) to expand market share. This combination of a few players, fierce price competition, and innovation efforts results in high competition in the IA industry.[95]

2. Threat of New Entrants - Low to Moderate.

Entering the IA business poses significant barriers. First, capital investment and technical know-how are substantial, as fermentation facilities and purification processes at scale must be implemented. The industry is highly specialized, and new entrants would need expertise in microbial strain development and process optimization to achieve competitive yields. Moreover, regulatory hurdles can also be high, especially in Europe (e.g., regulations on industrial biotech and usage of genetically modified microbes, e.g., Directive 2009/41/EC).[96] These factors make it difficult for new companies to start IA production from scratch. Additionally, existing producers have advantages, as they benefit from scale and experience. This indicates that established players could rapidly increase production, saturate the market and suppress prices to discourage potential entrants. From a market perspective, citric acid producers could theoretically pivot to IA production with minimal additional investment if conditions become favorable, since production organisms and fermentation conditions are comparable; however, academic research indicates that such a transition may not be straightforward in practice.[97] The relatively small market size at present is another hurdle, as a new entrant might not achieve profitable volumes in a short time. On the other hand, Central and Eastern Europe are noted as cost-effective manufacturing hubs with growth potential for bio-based chemicals.[98] If demand surges, due to, e.g., a breakthrough application or stricter green regulations, new regional players or joint ventures could emerge to utilize local feedstocks and skilled labor. However, until such scale is realized, the threat of new entrants remains low and only a few new projects have materialized in recent years, which often involve established firms or consortia rather than brand-new companies. Overall, high startup costs, incumbent advantages, and limited market rewards keep the threat of new entrants in the IA market weak.

3. Threat of Substitutes - High.

Substitution is a critical factor constraining the IA market. IA's value lies in replacing or reducing petrochemical inputs, but those incumbent petrochemicals are strong substitutes that, at the moment, are cheaper or more readily available. IA-based builders must offer regulatory or performance benefits to displace it. The availability of these cheap, well-established substitutes is a major factor restraining IA market, but it is also a chance. Furthermore, new bio-based substitutes are available, e.g. bio-based acrylic acid[99] or bio-succinic[100]/fumaric acids[101] which can compete for the "green" niche that IA targets. This means IA not only competes with fossil-derived chemicals but also with other renewable platform chemicals under development. However, the mitigating factor is the sustainability trend, as IA is non-toxic and renewable, so in applications where green credentials are desired or even requested, IA may be preferred despite a price premium. However, until IA achieves cost parity or unique performance advantages, the threat of substitutes remains high, as customers can and will choose alternative inputs for most applications if IA does not deliver a compelling value proposition.

4. Bargaining Power of Buyers - High.

IA buyers, typically chemical companies using IA to formulate polymers, resins, adhesives, etc., tend to have considerable pricing power. One reason is the choice of suppliers on the global market. Even though the producer base is concentrated, buyers can source IA from multiple Chinese manufacturers or a few Western suppliers, as the product is relatively standardized, typically targeting ≥99% crystalline form.[102] This ability to switch suppliers easily forces sellers to compete on price and terms to win contracts. Moreover, many buyers are large industrial firms (e.g. in the plastics or coatings sector) that purchase significant volumes, and their scale gives them negotiating power to demand discounts or services. The presence of viable alternatives greatly strengthens buyers' position, as they are not locked into purchasing IA at any cost from a single supplier. In Central Europe, buyers of IA can benefit from competitive import dynamics by obtaining quotes from both Asian exporters and local distributors, leveraging this competition to secure favorable pricing. Since quality and product differentiation among IA suppliers are minimal because the product is standardized, price and reliability are the key factors for buyers. All these conditions translate to high bargaining power for buyers, thus allowing lower prices or better terms and changing suppliers easily if their expectations aren't met.

5. Bargaining Power of Suppliers - Low.

In the context of IA production, "suppliers" refer to the providers of raw materials and inputs, primarily sugars or feedstocks used in fermentation (e.g., glucose from corn or sugar beets, molasses, etc.), but also yeast/fungal strains, nutrients, and energy. These feedstock suppliers have little power to dictate terms to IA producers. Sugar is a commodity, and there are many global and regional suppliers of fermentable sugars.[103] Producers can shop around for the lowest price or most convenient source. The economic viability of IA often hinges on using low-cost feedstocks, as studies emphasize that using local agricultural by-products or residues (instead of pure glucose) can (significantly) cut production costs.[93] Therefore, theoretically, IA manufacturers can achieve a certain level of flexibility if their process allows an easy substitution of the feedstock. If glucose becomes too expensive, they can change to molasses as an alternative. Feedstock market is highly competitive, and raw material prices are transparent, keeping supplier leverage in check. Likewise, other inputs (e.g., nutrients, fermentation equipment) are readily available from multiple vendors, even though fermentation equipment can be expensive. Many IA producers either develop microbial strains or source them via research partnerships, so they are not beholden to an external supplier for proprietary technology. Overall, because inputs are (to a certain extent) interchangeable and sourced from diverse competitive markets, suppliers cannot easily raise prices without risking losing business. As a result, the bargaining power of suppliers in the itaconic acid industry is low, with producers largely able to secure the inputs they need at market-driven prices, or if required, substitute input sources to manage costs.

4.6. European start-ups & SMEs in IA production and use

The European market for IA, with applications ranging from bioplastics to detergents, is still in its early stages. Despite growing interest in sustainable alternatives to petrochemical feedstocks, only a handful of companies in Europe are currently active in producing or applying IA. Overall, the commercial adoption in Europe remains limited due to high production costs. In Europe, a few strategic efforts led by industrial biotech firms and SMEs are targeting both production and application.

1. **European companies active in IA Production**

The 1st examples (1.1. Leaf Technologies, 1.2. Dutch DNA Biotech, and 1.3.Novamont S.p.A.) illustrate contributions made under the European project "Bio-QED - Quod erat demonstrandum: Fermentative production and scale-up for the production of 1,4-butanediol and itaconic acid with the aim of cost reduction and improved sustainability" from 2014 to 2017.[104]

1.1. Leaf Technologies (Lesaffre Advanced Fermentations, France)

Leaf is the biotech division of Lesaffre (a major French yeast manufacturer) focused on industrial fermentation for sustainable chemicals. Leaf operates like an SME under Lesaffre to develop new biotech processes. In 2015, Leaf entered the IA market *via* an R&D collaboration with Dutch DNA Biotech.[105,106] Leaf's goal is to create high-performance strains for producing IA from various sugars (including cellulosic hydrolysates) at a lower cost. This initiative was one of Europe's first serious attempts at IA strain development. Leaf provides expertise in fermentation scale-up and process optimization, exploiting Lesaffre's pilot facilities. While Leaf's partnership was R&D-stage, it signaled Europe's commitment to enabling local IA production. Leaf also explores integrating IA production in biorefineries (e.g., using second-generation feedstocks). Although Leaf does not yet produce IA commercially, its engineered strains and process know-how could be licensed or used to establish production when market conditions favor it.[105–107]

- **Key Focus**: Strain optimization for large-scale, economically viable fermentation
- **Relevance**: Decarbonization of industrial chemicals

1.2. Dutch DNA Biotech (The Netherlands)

Dutch DNA was a start-up founded as a spin-off from TNO in the Netherlands, specializing in filamentous fungal biotechnology. The company built a platform for genetically engineering fungi (like *Aspergillus* or *Trichoderma*) for high-yield production of enzymes and organic acids. Their expertise included constructing strains that tolerate inhibitory conditions and efficiently synthetize IA. In 2021, Ginkgo Bioworks (USA) acquired Dutch DNA, integrating its platform to broaden Ginkgo's strain offerings.[108] Built on Dutch DNA's foundation, advanced fungal strains are readily accessible for any company seeking to produce IA locally in Europe. Thus, Dutch DNA is a great example of a small European biotech whose innovation (in fungal strain engineering) became a driving force for a bio-based chemical value chain.

- **Key Focus**: Microbial strain development
- **Relevance**: R&D support for biomanufacturing platforms

1.3. Novamont S.p.A. (Italy)

Novamont, a scale-up in biochemicals and bioplastics, coordinated the EU-funded BIO-QED project, which validated pilot-scale IA production. The project marked a milestone by reaching fermentation volumes of 10 m^3 demo level. Novamont integrates such intermediates into the development of biodegradable materials. This validated the viability of European IA production and its use in biopolymer products.[109,110]

- **Key Focus**: Pilot-scale production and downstream integration
- **Relevance**: Bioplastics and EU innovation consortia

It should be noted that none of these companies appear in the REACH registration (≥ 10 kt to < 100 kt) in Q3 2025 (see 4.11. Supply chain analysis (EU-focused)).

2. **Companies Applying IA in their products**

2.1. Itaconix PLC (UK)

Itaconix is a specialty polymers company that has become a global leader in IA applications. The original incarnation, Itaconix (*UK*) Limited, traces its establishment to 2005 (originally as Revolymer), and continues as a UK-registered private limited company,[111] Being the world's only dedicated manufacturer of IA and itaconate-based polymers at commercial scale, Itaconix develops, produces, and sells plant-based ingredients for home care, personal care, and industrial uses. Itaconix's technology platform focuses on the versatility and safety of IA as a replacement for petrochemical polymers. Key products include: washing detergent polymers (as phosphate-free builders), odor-neutralizing polymers, and hair styling polymers, which they supply to larger partners.[112] Itaconix gained recognition for pioneering 100% bio-based polyitaconate in detergents, winning partnerships with Croda and Nouryon.[112,113] It was originally founded in New Hampshire, USA, but in 2016 it merged with UK-based Revolymer PLC and is now listed on the London AIM stock market.[114] With R&D in the UK, Itaconix has market leadership in non-phosphate detergent additives, odor control, and hair styling polymers using IA. Recently, Itaconix has expanded into the coatings realm with its BIOAsterix line (launched 2025) of functional monomers for paints, coatings, and adhesives.[115,116] This expansion marks Itaconix as a key innovator driving IA use into new sectors. Their growth underscores the viability of an SME focusing on this "niche" acid, IA. indeed, Itaconix's success is considered proof that high-performance, green chemistry can compete with incumbents. More information about Itaconix products is listed in **Table 3** in section 4.2. Producers and IA-based products.

- **Key Focus**: Sustainable polymer formulations
- **Relevance**: Cleantech and green consumer products

2.2 Van Loon Chemical Innovations (VLCI, Netherlands)

Van Loon Chemical Innovations (VLCI), based in Amsterdam, is an R&D services firm that provide predictive formulation science (Hansen Solubility Parameters, HLD-NAC) combined with high-throughput automated screening to accelerate and optimise product formulation across industries including coatings, polymers, personal care, household, agrochemicals, and pharmaceuticals.[117] Their contributions to projects like BioQED, applying high-throughput synthesis with IA to develop bio-based polymers and additives, such as rheology modifiers, surfactants, coalescents, and binders for coatings, adhesives, and personal care applications.[118] VLCI provides formulators, from startups to multinational companies, with data-driven development tools and workflows, delivering IP to clients and accelerating go-to-market timelines.[117]

- **Key Focus**: delivers predictive, data-driven formulation R&D with high-throughput automated screening
- **Relevance**: accelerates the commercialization of bio-based innovation

3. **Legacy and broader view**

Historically, Rhodia (France), which was acquired by Solvay S.A. in 2011 for €3.4 billion was the only European producer of IA.[119] However, due to limited domestic demand, Rhodia ceased IA production in France several years ago. This left Europe without domestic bulk production, and when Cargill and Pfizer (US) stopped their IA production China became the largest producer of IA, leading Europe to rely on imports from companies like Qingdao Kehai Biochemistry having an annual output capacity of 20,000 t.[120] Recently, there has been renewed interest in re-establishing IA production within Europe. For example, BASF invests in process development in the biotech sector,[121] and companies like Itaconix have achieved commercial success with IA-based products. Such activities suggest the potential for a revival of local production capacity.

A notable feature of the European market is strong cross-sector collaboration. Start-ups frequently partner with academic institutions (such as university spin-offs), government-backed initiatives e.g. in CBE JU projects), and large corporations through joint development agreements. This collaborative ecosystem supports innovation and helps mitigate the risks associated with scaling up new processes. For instance, the Leaf Technologies – Dutch DNA Technology partnership brought together industrial players and research institutes (such as TNO), while Itaconix's products have reached the market through partnerships with larger firms like Croda and Nouryon. These examples show how SMEs benefit from the distribution and production resources of major industry players. Moreover, EU funding programs and policy measures, including regulatory restrictions on certain petrochemical products, provide additional incentives and support for the growth of the European bio-based chemicals sector.[77,122]

4. **Market assessment and insights**

4.1. Limited adoption and fragmented supply chain

While promising, the European market for IA remains underdeveloped, and the number of companies actively integrating IA into consumer or industrial products is small. Most current activities are pilot-scale production or formulation R&D rather than full-scale commercialization. This limited uptake reflects:

- High production costs relative to Asia and petrochemical alternatives.
- The lack of end-user awareness or demand for IA-derived ingredients.

4.2. Strategic opportunities

Despite these challenges, several growth pathways are emerging:

- **EU Green Deal & circular economy through public-private collaborations**

  Policies promoting bio-based materials and carbon-neutral supply chains offer support for scaling IA production promoted through consortia that de-risk innovation and facilitate pilot-to-commercial transitions.[77,122,123]

- **Substitution potential**

  IA is structurally similar to acrylic and maleic acids, making it a promising candidate for replacing fossil-based monomers in many applications, e.g., for adhesives, coatings, and personal care products.[124–127]

Recommendations and emerging opportunities

1) **Need for demonstration projects –** more industrial-scale demonstrations are required to validate IA's cost-effectiveness and performance in diverse applications. With an expansion of pilot-to-commercial scale, projects like BIO-QED provide blueprints for bridging lab-scale success and market-scale manufacturing. Companies equipped with scalable fermentation and purification technologies will gain competitive advantages.

2) **Support for start-ups –** dedicated EU funding and innovation hubs could accelerate the emergence of start-ups focused on high-value derivatives or application development. Collaborative innovation hubs, like Circular Bio-based Europe Joint Undertaking (CBE JU) and other initiatives continue to offer platforms where SMEs can amplify their impact.

3) **Value chain integration** – encouraging vertical collaboration between producers, formulators, and end-users can help create stable demand and enable scale. By integrating actions into circular economy models, SMEs and start-ups are increasingly aligning their strategies with EU Green Deal objectives, creating room for IA to substitute fossil-derived materials in high-volume sectors.

Conclusion

Europe's IA market remains in an early stage, with only a handful of SMEs and start-ups engaged in production or use. The companies mentioned in this section represent critical nodes in a slowly maturing ecosystem. For IA to fulfill its potential as a sustainable alternative to fossil-derived chemicals, greater coordination, policy support, and downstream engagement will be essential. Presumably, the European market for IA is expanding, fueled by a convergence of sustainability objectives, technological breakthroughs, and dynamic start-up activity. European start-ups and SMEs play a critical role in application development, and companies like Itaconix have proven the commercial viability of IA/itaconate polymers in everyday products (detergents, cosmetics, etc.).[46,115] Biotech innovators such as Leaf Technologies and Dutch DNA Technology have addressed upstream challenges, engineering microbes aiming to make production more efficient and eventually cost-competitive. Across the value chain – from fermentation to formulation – companies like these have introduced technological innovations (new strains, new polymer chemistries, new products) that enlarge the scope of IA applications. Europe's IA applications include biopolymers (biodegradable plastics),[128] specialty chemicals (coatings, adhesives, resin additives),[116] cosmetics (hair and skin polymers), agriculture (fertilizer additives, hydrogels), while emerging in other fields like pharma and medical materials, providing a renewable, often safer, and versatile alternative to petrochemicals. Moreover, IA derivatives provide e.g. phosphate-free detergents[46] and formaldehyde-free adhesives with strong bonding.[129] These use cases align perfectly with Europe's regulatory direction and consumers' preferences, indicating a continued growth. Challenges remain, notably the need to further reduce production costs and (re)establish local European production capacity to ensure supply security. Currently, global production is sufficient but needs to be scaled for a major surge in demand. However, the groundwork laid by European SMEs and research suggests that Europe could develop its production facilities, e.g., integrated into biorefineries or backed by chemical majors. IA thus exemplifies a broader trend in

Europe's chemical industry: the shift toward a bio-based, circular economy model, led by innovative small and medium enterprises with support from policy and industry giants.

European startups and companies engaged in IA production depend greatly on (global) IA pricing, for which the key parameters shaping international price dynamics will be identified and evaluated in the following section.

4.7. Technological analysis of IA production

4.7.1. Fermentative Production Technologies

IA is predominantly produced via microbial fermentation, a method that has been used at industrial scale since the early 1950s.[130,131] The filamentous fungus *A. terreus* remains the most widely used industrial microorganism for IA production, due to its ability to tolerate low pH fermentation conditions and achieve relatively high titers.[18,132,133] In optimized batch or fed-batch fermentations, a natural wild-type strain of *A. terreus* can reach IA concentrations up to 150 g/L over a 10-day cultivation.[132] Industrial yields have been reported up to about 0.5–0.6 g IA per g glucose consumed[132], which approaches ~60% of the theoretical maximum. Maintaining the fermenter at pH ~3 is crucial in these processes to favor IA accumulation, as *A. terreus* produces fewer unwanted byproducts at low pH[132] and secretes (fully protonated, pk_a values 3.8 and 5.6 at 25 °C) IA under these acidic conditions[5,134].

1. **Feedstocks**

Traditional feedstocks for fermentative IA production are refined sugars. According to the academic literature and process patents, glucose remains the dominant substrate, followed by sucrose, starch hydrolysates, glycerol, xylose, and agro-industrial wastes. These feedstocks represent a balance between availability, yield, cost-effectiveness, and sustainability, highlighting ongoing research into more environmentally friendly and cost-effective sources.[67,15,135] **Table 4** shows an overview of the main feedstocks for IA production.

Table 4. Overview of a selection of feedstocks for the microbial production of IA.[67]

Microorganism	Feedstock/substrate	IA yield (g/L)
A. terreus DSM23081	glucose	129
A. terreus TN-484	glucose	82
A. terreus NRRL1960	sucrose	55
A. terreus TN-484	corn starch	58
A. terreus SKR10	sago starch	48
A. terreus MJL05	glycerol	28
Ustilago maydis MB215	glucose	45
Ustilago maydis MB215	xylose	28
Pseudozyma antarctica NRRLT-7808	sugars (general)	30
A. terreus IMI282743	palm oil mill effluent	6

To produce IA, the carbon source is metabolized *via* the tricarboxylic acid (TCA) cycle to *cis*-aconitate, which is, in *A. terreus*, converted to itaconate by *cis*-aconitate decarboxylase (CadA).[11] However, this microorganism is sensitive to impurities in raw feedstocks, such as trace metals like manganese, which need to be removed because they severely inhibit IA biosynthesis.[133,136] Thus, feedstock purity is important, often requiring a pre-treatment of raw materials. This reliance on pure feedstock increases costs and is a major factor in the overall economics of the process.[33,68] Recent research is applying other microorganisms, as well as exploring alternative feedstocks to reduce costs, including agricultural wastes or lignocellulosic hydrolysates, or even methanol as carbon sources for IA fermentation.[15,16,137] Using such renewable waste streams or C1 substrates can decrease production costs and improve sustainability if the (engineered) microorganisms can utilize them efficiently.

2. Downstream processing

After fermentation, IA, which is enriched in the culture broth, needs to be separated and purified. In conventional processes, the fungal biomass is first removed (e.g. by filtration) and then IA is recovered (from the filtered broth.[11,67] Different recovery methods for IA show varying efficiencies. Crystallization yields ~51% (97–99% purity) in fermented broths.[67] Likewise, precipitation achieves ~51% recovery, while pertraction and extraction combined yield ~50%. Reactive extraction from aqueous solutions is highly effective, with 73–99% recovery, and electrodialysis reaches 98% recovery. Adsorption methods (aqueous/glucose solutions), such as via basic ion-exchange resins, are the most efficient, consistently yielding 100% recovery. Overall, adsorption and reactive extraction outperform crystallization and precipitation in recovery efficiency.[67] However, crystallization methods are mostly applied on an industrial scale for economic reasons. The crystallization approach benefits from the low pH of the broth (IA is mostly undissociated, facilitating crystallization) and produces a high-purity product. However, crystallization is energy-intensive (requiring cooling or evaporation). To improve efficiency, alternative downstream technologies have been investigated, including chemical precipitation (e.g., forming calcium itaconate salt and then acidifying), liquid–liquid extraction, membrane separations, and adsorption processes.[138–140] Each method has advantages and disadvantages. For example, solvent extraction can selectively remove IA from broth but requires solvents and additional steps. In contrast, adsorption techniques, although relatively immature and thus associated with substantial processing costs, can achieve up to 100% purity of IA from aqueous solutions at high yields),[23,141] potentially allowing for its continuous removal during fermentation.[67] Research into *in-situ* product recovery aims to diminish product inhibition and boost productivity by removing IA as it forms.[142] Indeed, product inhibition is a consideration – while A. *terreus* can tolerate high IA concentrations (over 100 g/L); many other microbes have lower tolerance,[143] and therefore coupling fermentation with continuous IA removal (using membranes or adsorbents) could be a key innovation for these systems.

3. Process characteristics and challenges

A. terreus fermentation has some inherent challenges. One limitation is that *A. terreus* is categorized as a class 2 animal pathogen[144], and therefore biosafety precautions needed can complicate the regulatory approval for certain production setups. Moreover, its filamentous morphology leads to viscous broths and mixing/aeration difficulties, [132] but intensive agitation is needed for oxygen supply, as IA production is aerobic. However, the mycelial fungi are shear-sensitive, and hence strong agitation can damage the mycelia or cause clumping.[145] The requirement of dissolved oxygen is one factor contributing to relatively low volumetric productivity, and typical *A. terreus* batch fermentations reach productivities in the order of 0.3–0.7 g/L/h,[134] and thus, a fermentation can take over a week to reach maximal titers. Finally, by-product formation (such as citric acid or other organic acids) can occur if conditions are not optimal, and the fungus's metabolism can divert flux away from IA if, for example, trace minerals are present or if pH drifts upward.[6,7,131,133,136]

4. Current status

Despite these challenges, fermentative production with *A. terreus* remains the most established commercial route for IA production, as highlighted in peer-reviewed reviews and market analyses.[8,19,134] Several manufacturers, historically based in the US and now predominantly in

Asia (especially China), operate these fermentation processes at industrial scale. As of the early 2020s, global IA output is estimated in the range of several tens of thousands of tons per year, though data is not publicly disclosed; market reports suggest production in the 50-80k ton/year range.[135,146,147] This volume remains modest compared to major industrial chemicals like acrylic acid, reflecting IA's current niche but growing applications.[23] While the fermentation process is proven at scale, production costs are still higher than petroleum-based alternatives, limiting broader adoption in cost-sensitive applications. For instance, acrylic acid is a globally traded commodity with a market size of approximately USD 15.3 billion in 2024,[148] and hence with lower prices due to large-scale production and mature supply chains, while IA is a niche, bio-derived product with higher prices due to limited production capacity and more complex logistics. Prices for both acids vary by region, with Asia generally offering the lowest prices for acrylic acid. In detail, in July 2025, global acrylic acid prices ranged from approximately 0.98 USD/kg to 1.65 USD/kg, with higher values in North America and Europe and lower values in Asia, while IA prices ranged from about 1.25 USD/kg to 1.60 USD/kg in the same period, reflecting typically higher costs compared to acrylic acid across comparable markets.[64,149] Efforts to improve the fermentation process, e.g., through microbial strain engineering, the use of cheaper feedstocks, and process optimization, are ongoing in research and industrial development.[63,150]

4.7.2. Chemical Synthesis Route

Historically, IA was first discovered in 1836 among the products of citric acid dry distillation, a process that primarily forms itaconic anhydride, which can then be hydrolyzed to the acid itself.[151] For much of the 19th and early 20th centuries, chemical synthesis remained the only known route to IA. Therefore, a variety of chemical pathways were explored, but none became industrially viable. Herein, the pyrolysis of citric acid,[152] yielding both IA and citraconic acids (the latter as isomers requiring challenging separation) was the most investigated. Moreover, there is a techno-economic model for producing IA by catalytic condensation of dimethyl succinate and formaldehyde, using experimental reaction yield/selectivity data and lab-developed product recovery steps. For a plant making 18 million kg/year over a 10-year life, the model estimates about USD 40 million capital investment and a required IA selling price of 2.34 USD/kg to reach a 30% annual ROI. It concludes that feedstock cost is the largest cost driver, so improving succinate conversion and selectivity toward the intermediate citraconic acid most strongly improves economics, and it suggests this catalytic route could be lower cost than fungal fermentation under the study's assumptions.[153] Today, commercial IA is bio-based, and chemical syntheses are mainly of academic interest or limited to niche derivatives, not bulk production.

4.7.3. Fermentation vs. chemical production - a technical comparison

Both fermentative and chemical routes to itaconic acid (IA) have inherent advantages and drawbacks. A comparative summary is as follows:

1. **Feedstock and sustainability**

Fermentation utilizes renewable feedstocks such as liquified corn starch,[70] molasses from sugar beets,[154] and cellulose hydrolysates,[29] which potentially makes the process more sustainable, as in contrast, chemical synthesis typically relies on petroleum-derived inputs like isoprene or acetone, which means the process is dependent on the availability of fossil fuel and price volatility.

Advantage: Fermentation.

2. Process complexity

Fermentation is a one-step bioprocess, but it involves living cultures requiring strict environmental control (sterility, aeration, pH, nutrients). Chemical routes typically involve multi-step reactions (oxidation, isomerization) and subsequent purification stages. The equipment for chemical processes, such as reactors or distillation columns, is standard in the chemical industry, while fermentation requires specialized bioreactors and downstream separations. Both approaches are complex. However, fermentation takes place in a single vessel under mild conditions, whereas chemical routes are sequential, and often under high temperature/pressure and catalytic steps.

Slight advantage: Fermentation (fewer distinct unit operations).

3. Yield and selectivity

Microbial fermentation can be highly selective for IA. Modern strains of *A. terreus* can convert glucose to IA with yields of ~50–60%, with by-products minimized by controlling culture conditions.[134,155] Chemical processes often suffer from side reactions leading to lower selectivity and more complex mixtures. Fermentation does generate broth impurities (biomass, proteins), but these are generally easier to separate, e.g. via filtration, than the chemically similar isomers produced in chemical synthesis.

Advantage: Fermentation.

4. Production rate

Traditional *A. terreus* fermentations are relatively slow, typically taking several days, and have moderate volumetric productivity.[155] In contrast a chemical reactor could, in theory, produce IA continuously at a faster rate if a high-yield catalytic process exists, though no industrial-scale optimized chemical process currently operates. Fermentation productivity is improving with strain and process engineering (e.g., >0.7 g/L/h in fed-batch).[136] Chemical production could potentially achieve higher space-time yields if developed, as it would not be limited by microbial growth rates.

Advantage: Potentially chemical (if a viable catalytic process were developed), but currently, only fermentation is viable.

5. Economic factors

Fermentation needs to cover costs for feedstocks, sterilization, and downstream processing, e.g. crystallization in batch or fed-batch operations. Chemical processes, if they could use inexpensive precursors, might benefit from continuous throughput and economies of scale. However, poor yields and costly separations hold back chemical production methods. The need to remove citraconic acid or unreacted reagents in petrochemical routes are additional expense. Currently, fermentation has the economic edge for IA production, as microorganisms perform the synthesis using relatively cheap inputs (e.g., molasses, or sugars), and ongoing improvements continue to reduce costs.

Advantage: Fermentation (with ongoing improvements).

6. Environmental impact

A comparative Life Cycle Assessment (LCA) between chemical and biotechnological production routes for IA has not yet been published to our knowledge. However, fermentative IA production is widely regarded as more environmentally friendly, because it predominantly uses renewable, biomass-based feedstocks such as glucose[134,156] and emits CO_2 primarily through biological respiration and fermentation, which forms part of the short (biogenic) carbon cycle.[157] In contrast, the traditional chemical synthesis of IA would involve petro-based resources and harsher chemical reagents, potentially resulting in a larger environmental impact.

Advantage: Fermentation (). Note: fermentative processes are energy-intensive and therefore, the environmental impact strongly depends on the energy source and whether it's generated from renewables or derived from petroleum-based fuels..

7. Summary

The comparison of fermentative and chemical IA production routes is summarized in **Table 5**.

Table 5. Comparison of fermentative and chemical production routes for IA.

Category	Fermentative route	Chemical route	Advantage
Feedstock & sustainability	Uses renewable biomass (e.g., sugars from corn, beets, cellulose hydrolysates)	Depends on fossil-based inputs (e.g., isoprene, acetone)	Fermentation
Process complexity	One-step bioprocess in a bioreactor; mild conditions; requires environmental control	Multi-step (oxidation, isomerization); high-temp steps; standard chemical equipment	Slight advantage: Fermentation
Yield & selectivity	High selectivity (~50–60% yield); manageable by-products like biomass and proteins	Lower selectivity, more side reactions, and complex mixtures	Fermentation
Production rate	Moderate; several days; improving with strain/process optimization (>0.7 g/L/h)	Potentially faster with continuous processing High-yield catalysts needed (none currently viable)	Potentially chemical, but currently fermentation only
Economic factors	Cost-effective using cheap feedstocks (e.g., molasses); improving efficiency despite batch limitations	Continuous production possible; but hampered by low yields and expensive purification	Fermentation (currently)
Environmental impact	Renewable feedstocks; part of short carbon cycle; fewer emissions	Petroleum-based inputs; potentially harsher reagents and higher environmental burden	Fermentation (energy use not assessed)

Fermentation holds the advantage in the current state-of-the-art, which is why industrial IA is produced biologically. The main disadvantages of fermentation are its sensitivity (microbes require specific conditions and can be inhibited by impurities) and high costs for processing requirements. If an innovative chemical synthesis were discovered (e.g., a one-step catalytic process from cheap feedstocks or directly from CO_2), it might compete with fermentation. However, given the advances in metabolic engineering and bio-process optimization, fermentation is likely to maintain its dominance.

4.7.4. Innovations and recent developments in IA technology

Significant innovation is underway to address the limitations of the traditional process and to expand the production of itaconic acid. Key areas of development include (i) metabolic engineering of microorganisms, (ii) process optimization, (iii) alternative feedstocks, and (iv) derivative production:

1. Strain improvement and metabolic engineering

Traditionally, *A. terreus* is the main IA producer. Metabolic engineering, such as overexpression of key genes (e.g., *cadA*, *mttA*, *mfsA*) has boosted yields. Non-traditional hosts like *Aspergillus niger* (engineered for IA, achieving a 20-fold increase)[158–161], *Saccharomyces cerevisiae*,[162,163] *Yarrowia lipolytica*,[12,13] and *E. coli*,[17] even though at lower yields, are also explored. Synthetic biology tools, e.g., CRISPR/Cas9 are accelerating strain optimization. Natural producers *Ustilago maydis, Ustilago Rabenhorstina,* and *Ustilago cynodontis* are promising due to their tolerance of higher pH and complex substrates and have already been engineered up to >100 g/L titers.[14–16] *Corynebacterium glutamicum*, a workhorse of amino acid fermentation, has been engineered to produce itaconate, leveraging its tolerance to high concentrations and ability to grow on lower-cost media.[164] While *C. glutamicum*'s titers are not yet industrially competitive, it benefits from being a generally recognized as safe (GRAS) organism and having well-established fermentation technology (from lysine production). Another intriguing host is *Komagataella phaffii* (formerly *Pichia pastoris*), a methylotrophic yeast, which was engineered to produce IA from methanol as the sole carbon source by integrating the *A. terreus cadA*, *mttA*, *mfsA* genes and optimizing the expression, obtaining an IA titer of 55 g/L in under 5 days with a yield of 0.24 g IA per g methanol.[137] This approach offers a future route to produce IA directly from a C1 feedstock derived from CO_2, potentially bypassing agricultural sugars entirely. Though the titers (55 g/L) are somewhat lower than sugar-based fermentations, this line of research could decouple IA production from arable land use.

2. Process engineering and bioreactor innovation

To complement strain improvements, process engineers are optimizing fermentation modes. Fed-batch processes with pulsed or continuous feeding of substrate have been used to reach higher IA concentrations without substrate inhibition.[132] In general, there is a great interest in continuous fermentation of organic acids, such as IA, to increase productivity and reduce downtime between batches.[26,156] Another innovation is adaptive control of pH. While *A. terreus* requires a low pH, some engineered strains (like *Ustilago cynodontis Max pH* variant) can produce IA at moderate pH (e.g., 5–6).[15] However, higher pH fermentations typically require neutralizing agents to control pH, a trade-off that produces salt waste. Thus, maintaining low pH fermentation is preferred if the organism can tolerate it.

3. Downstream process improvements

Being crucial for economic production, innovations in downstream separation are also emerging. For instance, *in-situ* product adsorption by resins or other absorbent materials directly in the fermenter, or recirculating the fermentation broth through an adsorption column, can continuously remove IA, thus preventing inhibitory levels and potentially simplifying purification, as IA can be desorbed in a concentrated form.[11,67,68] Membrane-based technologies like nanofiltration or electrodialysis are being tested to selectively separate organic acids from broth with lower energy input than evaporation.[165] Another strategy can be the integration of the fermentation with downstream units in a biorefinery concept, where multiple outputs are obtained, e.g., using residual biomass or co-products for energy or other chemicals, thereby improving overall economics.[166]

4. Alternative feedstocks

Alternative feedstocks are gaining attention as sustainable and cost-effective replacements for conventional sugars, like glucose. Among the most promising are molasses, a byproduct of sugar beet processing, thick juice, the sugar syrup from sugar refining, and crude glycerol, a major biodiesel industry byproduct. Ustilaginaceae fungi, such as *Ustilago maydis* and *Ustilago cynodontis*, have proven particularly robust in using these complex substrates, overcoming challenges like impurities, high nitrogen content, and osmotic stress that hinder traditional producers like *A. terreus*. For example, *U. maydis* efficiently metabolizes sucrose and fructose in molasses, achieving competitive yields (up to 0.4 g/g) and titers (over 37 g/L), while adapting to the varying carbon-to-nitrogen ratios typical of industrial byproducts. Crude glycerol can be converted into IA by engineered *Ustilago* strains, with fed-batch processes reaching high titers (74.5 g/L) and yields (0.7 g/g), and even higher performance when combined with molasses in a two-phase fermentation strategy. Thick juice has also been used successfully with *U. cynodontis*, supporting high-productivity fermentations (106.4 g/L, 0.7 g/L/h) without the need for costly pretreatments.[14–16,154,167] While *A. terreus* can utilize a variety of carbon sources such as molasses[9], starch-based substrates[10], and xylose (major monomer in HC) [26,33,133] for IA production, extending this approach to lignocellulosic biomass[168] introduces additional complexities, as it requires pretreatment to release fermentable sugars[31] and introduces inhibitors that can hinder microbial growth. These alternative feedstocks not only potentially reduce raw material costs but also enhance the sustainability of IA bioproduction by valorizing agricultural and industrial waste streams. While promising, lignocellulosic feedstocks remain less mature for industrial IA production compared to sugars.

Figure 6 provides a summarized overview of the key aspects of the technological analysis of the IA production, highlighting feedstocks, fermentation, downstream processing, and current status with future perspectives.

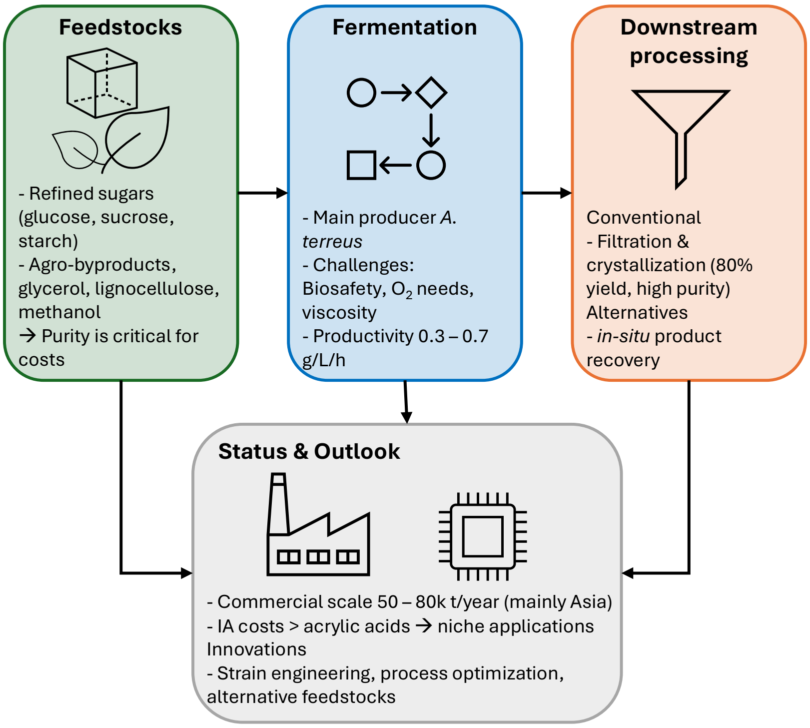

Figure 6. Overview of the key aspects of the technological analysis of the IA production.

4.7.5. Potential Disruptive Technologies

A disruptive development would be a hybrid process or an alternative route that lowers cost or improves sustainability.

1. **Hybrid fermentation–electrochemistry**

Coupling bioprocessing with downstream electrochemical steps, e.g, in a salt-free, energy-efficient downstream process combining low-pH fermentation, reactive extraction, and electrochemical separation to recover >99% pure itaconic acid with >90% yield and minimal waste, could overcome key fermentation and downstream limitations.[169] Although still in the early stages of investigation, this approach opens the door to plug-and-play integration of electrochemical solutions with fermentations.

2. **Direct CO_2 fixation pathways**

No natural microbial pathway generates IA directly from CO_2. However, synthetic-biology toolkits can overcome this. In this context, two parallel tracks are emerging:

Photoautotrophic chassis

Cyanobacteria can be engineered to redirect their carbon flux toward dicarboxylates. Inserting the *cis-aconitate decarboxylase* (CadA) combined with transporters could, in principle, create sunlight-driven IA factories.[170,171]

Chemolitho-autotrophic platforms

Formate- or hydrogen-oxidizing bacteria offer high volumetric uptake rates of CO_2 and are being refactored with tricarboxylic-acid shunts.[172–174] Further metabolic modification, e.g. the addition of the *trans-aconitate decarboxylase Tad1* from *Ustilago maydis*[175] could enable the production of IA in these microorganisms.

Overall, these strategies require further strain engineering, an improved holistic process design, integrating fermentation, *in-situ* recovery, and downstream purification. Each pathway is validated at a small scale, indicating the potential to enter a diversification phase for which biology, electrochemistry, and catalysis may co-evolve. If pilot campaigns translate these methods into integrated flowsheets, disruptive cost and carbon-intensity reductions move from speculative to plausible.

4.8. Process scalability and Economic Viability

Scalability

The industrial production of IA has already been proven with *A. terreus* in standard fermentation equipment. Facilities in China and other regions operate fermenters of tens or even hundreds of cubic meters. *A. terreus*' fermentation has the advantage of operating at around pH 2, hence being manageable with stainless steel with proper grades or coatings, while minimizing contamination risk. Reported industrial process up to 160 g/L IA titers in a multi-stage pulsed-batch fermentation, demonstrating high concentrations at scale.[132] The scale-up of filamentous fungi processes, however, comes with challenges: aeration and agitation become more difficult in large tanks due to oxygen transfer limits, increased broth viscosity, and heterogeneity of the system.[176,177] Despite design strategies such as baffles, specialized impellers, and fed-batch feeding to control viscosity (by limiting peak biomass) have been developed to minimize these challenges,[178,179] large-scale fermentations for products like IA struggle due to unfavorable morphological changes, such as excessive mycelial clumping with filamentous fungi, making process control and cost management challenging.[180,181] Therefore, robust non-filamentous hosts (e.g. yeasts or yeast-like fungi, such as *Ustilago cynodontis*) provide a natural morphology that results in improved process rheology, simplifying scale-up. Lab-scale experiments (e.g., *U. cynodontis* in 2L reactors) have shown promising results,[15] and scaling up toward industrial volumes must be the focus of further research. The ability of these strains to utilize impure, unrefined substrates could reduce upstream processing costs. However, at large volumes, downstream equipment, such as crystallizers and filtration systems, becomes a major cost and scaling constraint. Consequently, integrated process designs that couple fermentation with in-line separation (ultrafiltration, continuous adsorption) are aimed at improving efficiency and reducing capital investment in both upstream and downstream processes.

Economic viability

The economic viability of IA production hinges on achieving competitive production costs relative to alternative products (and relative to the selling price of IA). Historically, IA has been more expensive to produce than analogous petrochemicals, which kept its market volume modest. Key cost factors include:

- feedstock costs
- fermentation yield/productivity
- downstream processing cost
- scale

Feedstock is among the largest cost components, as pure glucose or sucrose is required, which can contribute significantly to costs. As a result, there is a substantial economic incentive to optimize IA fermentation processes by incorporating lower-cost carbon feedstocks. For example, using agricultural byproducts or low-grade molasses without yield loss reduces the material cost per ton of IA significantly. Herein, thick juice (a less refined sugar stream, used by Ustilaginaceae as a substrate for IA fermentation)[15] is economically promising because it bypasses refining costs compared to food-grade sugar. Improving the yield (conversion efficiency) directly lowers cost and yields closer to the theoretical maximum leading to less sugar "wasted" and fewer byproduct(s). Current yields of about 0.5–0.6 g/g are already efficient but still provide the potential for savings. Similarly, boosting productivity (g/L/h) reduces fermentation time and increases fermentation output, hence reducing fixed costs. Achieving titers >100 g/L IA is also crucial economically, with high titers requiring fewer cycles of downstream crystallizations, and hence more recovered product per batch, which increases the overall economic performance of the process. This goes along with innovation in process and strain development (such as engineered microbes that efficiently utilize cheap substrates) as the driving improvements in IA feasibility, as well as downstream integration (e.g., producing value-added IA derivatives like bio-based polymers and leveraging fermentation co-products), which can significantly increase profitability beyond commodity IA sales.

A great current challenge is the market price of IA. New technological development can significantly reduce the costs, which can potentially expand the market volume, making IA a more attractive substitute for other chemicals. Today's IA market is valued at roughly USD 100 to 110 m, and is expected to grow as bio-based chemicals demand rises.[19] Economies of scale can reduce costs, but scale-up is often hampered by uncertain market demand. As demand for bio-based chemicals grows, larger plants become more feasible, potentially unlocking cost parity or even advantages over petrochemical routes. Once established, economies of scale would improve viability, as larger plants (>20,000 tons per year capacity) can achieve lower per-unit costs due to more efficient use of equipment and utilities.

From a financial perspective, new entrants in IA production are focusing on value-added derivatives (such as IA-based polymers and resins) to justify investments. For instance, companies are making bio-based superabsorbent polymers and detergents from IA, which have a higher profit margin than selling commodity IA itself. These downstream products create additional revenue streams and can improve the overall profitability of IA production sides. Additionally, co-products from fermentation (like biomass for animal feed or other organic acids) could be used to improve the process economics.

For break-even analysis, a techno-economic study needs to consider the capital expenditure (fermenters, separation units, etc.) *versus* the operating costs (substrate, energy, labor) and project at what production scale and price the venture becomes profitable. Reducing feedstock cost (through cheap substrates) and increasing the yield of pure IA at low downstream costs are impactful levers. For example, substituting half of the glucose with an agricultural waste hydrolysate reduces material costs substantially, but only if the organism can use it, resulting in similar yields of IA. Similarly, any improvement in yield would translate to a reduction in cost (all else equal). These improvements, when compounded with larger-scale operations, suggest that fermentation-based IA is steadily becoming more economically viable. Indeed, with continued innovation, the process is expected to reach a point where IA can economically compete with some traditional petrochemicals, especially as sustainability considerations are present in the marketplace.

European Perspective and Developments

Globally, Asia (particularly China) leads the commercial IA production, while Europe is playing a strong role in research and innovation for IA technologies. The EU, driven by its bioeconomy and sustainability goals, has funded several projects to advance fermentative production. For example, the Bio-Based Industries Joint Undertaking (BBI JU) and its successor Circular Bio-based Europe Joint Undertaking (CBE JU) programs have supported projects focusing on non-food feedstocks and novel microbes for a broad range of bio-based products.[77,122,182] In addition, national initiatives are increasingly aligned with domestic implementation targets of the European Green Deal, driving demand for compliant technologies and services, e.g. by developing a regional biorefinery concept using *Ustilago* strains to produce IA with sugar beet-derived feedstock (thick juice).[15] By using locally available feedstocks (like beet molasses or wood hydrolysates), or even valorizing agricultural residues, European efforts aim to create sustainable IA supply chains that reduce reliance on imported sugars or petrochemicals.

Europe has emerged as a hub of innovation in metabolic engineering approaches aimed at optimizing IA biosynthesis. Institutes in Germany, the Netherlands, and Austria have published many recent breakthroughs (e.g., the *Ustilago cynodontis* high-pH strain from RWTH Aachen/FZ Jülich)[15], and the *Komagataella phaffi* methanol-based IA production from BOKU/Austrian Centre of Industrial Biotechnology. These advances lay the groundwork for scale-up within the EU, pointing toward commercialization in Europe, as shown by a 2023 study that presents a holistic biorefinery approach for bio-based IA production using *Ustilago* and thick juice from sugar beets, showing that process yield and aligned pH control are key to improving techno-economic feasibility despite challenges from substrate impurities.[22] Europe's focus on green chemistry and circular economy provides the use of biobased building blocks, such as IA in new products (e.g. biodegradable polymers, bio-based coatings). This could create market conditions to promote the establishment of local production facilities for IA in the EU to supply these emerging applications. It's noteworthy that European policies favoring low-carbon products indirectly benefit IA, for instance, initiatives to reduce the carbon footprint in plastics could increase demand for IA-based monomers. European start-ups and companies (such as Itaconix, with R&D and manufacturing in the UK) are already formulating IA-derived polymers for detergents and hygiene products, leveraging the "bio-based" appeal.[46]

In summary, Europe's role is currently more on the innovative and early-stage scale-up side rather than bulk production, but this could change shortly. By developing processes that use Europe's feedstock strengths (like lignocellulosic biomass or waste streams) and by capitalizing on EU funding for sustainable tech, European players aim to advance in technology and possibly set up competitive IA production units. This regional focus complements global developments: a scenario can be envisioned where European technology for efficient IA fermentation is licensed or implemented worldwide, making the overall IA industry more robust and economically viable.

By enabling the global licensing or adoption of advanced fermentation technologies developed in Central Europe, the international IA industry becomes more resilient and economically viable as an outcome of the region's robust regulatory environment that enforces high standards for safety and sustainability.

4.9. Regulatory Environment in Central & Western Europe

Key regulations (regional and global) affecting IA and related products are discussed, and their implications for fermentation-based manufacturing (including sustainability criteria, carbon footprint, and waste management) are highlighted.

4.9.1. Key environmental & chemical regulations in Europe

The production of IA in Europe is subject to a complex framework of environmental and chemical regulations designed to ensure sustainable manufacturing, protect human health, and align with the European Union's ambitious climate and circular economy goals.

- **EU REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)**

REACH is the cornerstone of EU chemical regulation, requiring manufacturers or importers to register substances produced or imported > 1 ton/year and to demonstrate their safe use. Note: IA is not on the REACH Candidate List or subject to Annex XIV authorization, but it must be registered under REACH if usage exceeds 1 ton/year. Thus, IA and any derived products must be registered under REACH, meaning companies need to supply data on toxicity, environmental impact, and risk management. This ensures a high level of health and environmental protection, but imposes significant compliance costs and testing requirements. Notably, polymers are currently exempt from registration under REACH, but monomers like IA are not.[183]

- **CLP Regulation (Classification, Labelling and Packaging)**

Aligned with the UN Globally Harmonized System (GHS), the CLP regulation mandates classification of chemical hazards and appropriate labelling is generally regarded as having low toxicity due to its biodegradability and low hazard potential, which is considered in the classification under the CLP regulation. IA is classified as an irritant (not a major toxic hazard). Thus, any IA-based product must be labeled for irritation, if applicable, and safety data sheets must be provided. Compliance with CLP ensures consistent hazard communication across Europe and globally.[184]

- **Environmental Directives (Industrial Emissions and Pollution Control)**

The revised Industrial Emissions Directive (IED 2.0), effective from 4 August 2024, regulates pollution from around 75,000 large industrial and livestock installations in the EU. It enforces stricter emission limits, resource efficiency, and digital permitting based on Best Available Techniques (BAT). A new Innovation Centre (INCITE) supports the uptake of cleaner technologies. The directive also boosts public access to environmental data and introduces tougher penalties, including fines up to 3% of annual EU turnover for serious violations. A fermentation plant producing IA, for example, must control emissions (such as volatile organic compounds, odors, or CO_2) and treat wastewater and solid residues following permit conditions. The IED (formerly IPPC Directive) enforces a high standard of environmental performance, aligned with global best practices for pollution prevention. Operators must implement waste management and energy efficiency measures to comply with permit limits, which drives cleaner production methods.[185,186]

- **Waste Management and Chemical Waste Regulations**

The EU's Waste Framework Directive (Directive 2008/98/EC) sets a waste hierarchy favoring prevention, reuse, and recycling. Fermentation by-products (e.g. residual biomass or spent broth) are classified as bio-waste and should ideally be valorized rather than disposed. Companies are encouraged or even required by national laws to recover useful materials or energy from fermentation residues (for instance, using biomass waste for biogas or as fertilizer if safe). Hazardous waste regulations apply if any process chemicals or by-products are classified as hazardous.[187,188] EU rules require separate collection or source recycling of bio-waste, including fermentation residues, and that separately collected bio-waste cannot be incinerated or landfilled, aligning with Landfill Directive 2018/850.[189] Additionally, the Water Framework Directive (Directive 2000/60/EC) and local wastewater discharge regulations will govern effluent treatment for fermentation plants to protect waterways.[190,191] Overall, stringent EU waste and water rules push firms to implement robust waste treatment and to recycle or recover waste streams, supporting the circular economy.

- **EU Green deal and climate policies**

European climate and environmental policies establish a comprehensive regulatory framework that significantly shapes the operations and development of the chemical industry, including fermentation processes. The European Green Deal sets ambitious sustainability targets, including achieving climate neutrality (net-zero emissions) by 2050 and a "zero pollution" environment.[192,193] Under this framework, the EU has tightened regulations on industrial emissions and is integrating climate objectives into policy. For example, legislation on issues such as carbon emissions is being developed, signaling future requirements for more sustainable products. Globally, the Paris Agreement commits the EU and others to reduce greenhouse gas emissions.[194] In response, the EU's Fit for 55 package and Climate Law mandate a 55% cut in greenhouse gas emissions by 2030 from 1990 levels.[195] These climate commitments indirectly pressure chemical manufacturers to cut the carbon footprint of their processes and products. Notably, the EU Emissions Trading System (ETS) imposes costs on CO_2 emissions for large emitters. While fermentation-derived CO_2 (being biogenic) is generally considered carbon-neutral, any fossil energy used on-site, e.g., for steam, or process emissions, could fall under the ETS. There are ongoing discussions to possibly include more sectors, like waste incineration, and potentially some chemical processes in the ETS.[196] Overall, Europe's climate policy acts as a global benchmark, encouraging low-carbon technologies such as bio-based production.

- **Chemicals Strategy for Sustainability (CSS)**

As part of the zero-pollution ambition, the EU launched the CSS in 2020. This strategy aims to boost innovation for safe and sustainable chemicals[197] and includes measures such as stricter control of hazardous substances, developing criteria for "safe and sustainable-by-design" (SSbD) chemicals, and simplifying regulatory procedures. While not being a law, CSS guides future updates to REACH and other laws. For a bio-based chemical like IA, the CSS is favorable, as it promotes chemicals that are inherently safer and greener throughout their life cycle.[198] EU policy is moving towards rewarding chemicals and processes that have lower toxicity, lower environmental impact, and contribute to circular economy objectives.

- **Other relevant regulations**

Europe also enforces specific regulations that can impact niche applications of IA. For example, if IA derivatives are used in detergents, they must comply with the EU Detergent Regulation and biodegradability requirements. EU environmental rules have indirectly boosted interest in IA, as phosphate-based builders in detergents are limited, which creates a need for sustainable substitutes.[199,200] Additionally, regulations like the Seveso III Directive 2012/18/EU[201] for industrial accident prevention and occupational safety laws ensure that fermentation facilities handling large volumes of chemicals (even relatively low-toxicity ones like IA) have robust safety measures. At the global level, conventions such as the Basel Convention govern the cross-border movement of chemical wastes, meaning any hazardous waste from production must comply with international transport and disposal rules.[202]

In summary, central and western Europe's regulatory environment is characterized by strict chemical safety laws (like REACH/CLP) and environmental regulations that both constrain and catalyze the chemical industry. Companies producing IA or products from it must navigate these laws, which ensure high environmental standards and can create market advantages, but it also raise compliance hurdles compared to regions with laxer regulations.

4.9.2. Sustainability, carbon footprint & waste implications for fermentation-based processes in the EU

- **Sustainability criteria and renewable feedstocks**

European policies actively promote the use of renewable, bio-based raw materials, but they also require that these materials be sourced sustainably. Under the EU's Sustainable Carbon Cycles initiative, the Commission has set a target for at least 20% of the carbon used in chemicals and plastics to come from sustainable non-fossil sources by 2030. This includes carbon from biomass, recycled materials, and captured CO_2, supporting the broader goal of defossilizing the chemical sector.[203] Producing IA from plant-derived sugars aligns well with this goal, as it replaces petrochemical carbon with biogenic carbon. However, sustainability criteria also mean companies must consider the full life-cycle impact of their feedstocks. Using first-generation biomass, such as crops or sugar, raises concerns about land use, food competition, and biodiversity. Other EU policies, such as the Renewable Energy Directive's sustainability criteria for biofuels,[204,205] favor waste or residue-based feedstocks and avoid sourcing from high-biodiversity areas. While those biofuel regulations do not regulate chemical production, the principles must be applied. Thus, a fermentation plant using agricultural waste or non-food biomass may face fewer sustainability objections than one consuming edible glucose syrup. Therefore, companies aim for certifications like ISCC (International Sustainability and Carbon Certification)[206] to prove their feedstocks meet environmental and social criteria. In short, fermentation processes are encouraged to use sustainable feedstocks, as that can help in marketing products as "green" in a European market with conscious consumers.

Fermentation processes that utilize sustainable, non-fossil feedstocks align with EU climate and circular economy objectives, supporting the shift toward low-carbon, resource-efficient production. Such practices not only reduce environmental impact but also enhance transparency and traceability, which are key factors for regulatory acceptance and alignment with emerging EU sustainability standards. In Europe's increasingly eco-conscious market, products made with renewable, non-fossil inputs are positioned as "green" solutions, offering a clear competitive edge and stronger appeal to environmentally aware customers.

- **Carbon Footprint Reduction**

A major advantage of fermentation-based chemicals is the potential for lower greenhouse gas (GHG) emissions relative to traditional petrochemical processes, as demonstrated in a studies by the EU's Joint Research Centre showing that emerging bio-based products have about 45% lower GHG emissions over their life cycle than their fossil-based counterparts.[207] A GHG reduction is crucial in the context of EU climate goals and can help companies meet corporate CO_2 reduction targets. Additionally, emissions from fermentation, which are mainly CO_2 released by microbes, are biogenic and, thus, are not fossil CO_2 emissions. CO_2 emissions from fermentation are typically classified as biogenic and are therefore reported separately from fossil CO_2 emissions. As such, they are considered carbon-neutral and are generally not subject to emission reduction obligations under national greenhouse gas inventories or schemes like the EU Emissions Trading System (EU ETS), provided the biogenic origin is appropriately documented.[196] However, the carbon mitigation potential of fermentation-based processes depends not only on the biogenic nature of the CO_2 emissions but also on the integration of renewable energy sources and overall process efficiency. If such processes rely on fossil-based electricity or generate significant waste streams, the net GHG benefits may be substantially reduced. The European Commission's Product Environmental Footprint (PEF) methodology, which is designed to standardize environmental impact assessment across product categories,[208] aims to drive manufacturers to confirm claims of carbon footprint reduction through standardized, verifiable LCAs conducted on a cradle-to-gate or cradle-to-grave basis. Fermentation technologies that can demonstrate net CO_2 emission reductions, when verified through robust LCA, are likely to be regarded positively under EU sustainability regulations, such as the EU Taxonomy for Sustainable Activities and forthcoming Corporate Sustainability Reporting Directive (CSRD) requirements. Such compliance can also enhance positioning within value chains subject to increasing environmental due diligence, offering both regulatory assurance and reputational value.[209,210]

- **Environmental Performance and Waste Management**

Fermentation-based production has a different waste and pollution profile compared to petrochemical processes. Generally, it produces fewer toxic by-products and operates at milder conditions, which can simplify pollution control. The European Commission notes that using fermentation and biocatalysis instead of traditional chemical synthesis can increase process efficiency, decrease energy and water use, and reduce toxic waste.[211,212] IA fermentation, for example, does not require toxic catalysts or harsh solvents, so hazardous chemical waste is minimal, which supports compliance with EU waste and water management regulations. A reduction in hazardous waste simplifies handling procedures and lowers associated disposal costs. Nonetheless, fermentation is not waste-free, and companies must manage by-product streams, such as microbial biomass and spent growth medium.

The (fungal) biomass remaining after the fermentation of sugars to IA may be rich in proteins and nutrients. Under EU waste legislation and circular economy principles, companies are encouraged to valorize such by-products, where safety and regulatory conditions allow, by converting them into animal feed, fertilizer, or processing them via anaerobic digestion for biogas production.[188,213,214] Where reuse cannot be achieved, the material must be treated as waste and managed following the regulations for safe disposal. As many EU countries prohibit landfilling of untreated organic waste, the biomass would likely need to be composted, utilised for energy recovery, or subjected to another appropriate treatment process. Likewise, wastewater from the fermentation contains organics, nutrients, etc., and must meet discharge standards. Companies can integrate water treatment units, e.g., anaerobic digesters or aerobic treatment, to comply with the Water Framework Directive limits.[190,215] Air emissions from fermentation are generally limited, mainly CO_2 and possibly odors or volatile compounds. Local regulations may require the implementation of odor control measures in cases where the facility emits perceptible smells, and in such instances, biofilters or scrubbers may constitute Best Available Techniques (BAT).

In sum, EU regulations push fermentation facilities to adopt comprehensive waste management, which includes valorizing bio-waste streams where feasible and treating any effluents aligning with the EU's circular economy agenda. Yet despite comprehensive EU regulations, implementation varies significantly across member states, with recyclable waste still often landfilled, though this practice must cease by 2030. Unlocking the untapped potential of biogenic waste for high-value chemical production requires extensive research into collection, standardization, transformation, and regulatory adaptation, positioning waste as a key resource in the circular bioeconomy.[226]

- **Safety and Genetically Modified Microorganism (GMM) Considerations**

If fermentation uses genetically modified microorganisms (GMM), which is a common approach to increase yields or favor other process parameters, EU GMM regulations apply. Although this falls under biosafety regulation rather than environmental law, this regulatory framework substantially influences the design and operation of fermentation processes. Specifically, Directive 2009/41/EC on the contained use of genetically modified micro-organisms (GMMs) demands the notification to and approval from competent authorities for activities that include the storage, transport, destruction, and disposal of GMMs. Compliance with these biosafety rules, including validated waste inactivation procedures, is a necessary precondition for obtaining authorization to operate a fermentation facility using GM strains in Europe. Therefore, the contained use of the GMMs Directive (2009/41/EC) requires stringent containment measures, risk assessments, and possibly public notification for industrial use of GMMs.[96] This can add to operational costs, but it ensures environmental and health safety by preventing any modified strain from an unintentional release into the environment.

- **Sustainable Product Standards**

Europe also encourages end-product sustainability. For instance, products made from IA, such as bio-based plastics or resins, might aim for ecolabels or certifications. The EU Ecolabel[216] or national eco-labels can be awarded if products meet criteria like a high bio-based content with a lower environmental impact and recyclability. Moreover, CEN has already developed criteria for "bio-based content", standards to measure the bio-based carbon content of products (EN 16785). They ensure safety, quality, and environmental performance, and once adopted, become mandatory national standards that support sustainable product development and market consistency.[217] While voluntary, these standards and labels are tools developed by consensus to support industry, safety, and policy goals, and thus their use is often essential for demonstrating compliance with legal or market requirements. Therefore, they create market incentives for fermentation-based products to meet certain sustainability thresholds, like a minimum % of renewable carbon or certain lifecycle emission savings. Additionally, under the EU Taxonomy for Sustainable Finance,[218] which serves as a classification system designed to guide sustainable investments, the production of chemicals can be considered environmentally sustainable if specific criteria are met to reach the objectives of the EU Green Deal.[192] These criteria typically require that the activity makes a substantial contribution to environmental objectives, such as reducing greenhouse gas (GHG) emissions, and that it does not cause significant harm to other objectives, including pollution prevention and the protection of ecosystems. To qualify, the production process must demonstrate meaningful impact in this context and comply with rigorous safeguards against pollution and adverse ecological impacts. The European Commission and stakeholders continue to discuss sector-specific implementation, and postponements or adjustments to the adoption of technical criteria for chemicals have been noted in authoritative sources.[218] A fermentation process, e.g., for the production of IA, that demonstrates to reduce emissions and uses sustainably sourced biomass could qualify, may thereby attract green investment funds or loans at preferential rates. This shows how financial regulations in Europe are indirectly moving chemical production toward processes like IA fermentation, if they improve sustainability criteria. Notably, the environmental benefits of fermentation are not automatic, as regulators and stakeholders expect proof. Life-cycle assessments are often requested to confirm that a bio-based process reduces emissions and pollution when all factors, e.g., land use for agriculture, processing, etc., are considered. For example, an analysis of 98 bio-based products shows an average 45% reduction in greenhouse gas emissions compared to fossil alternatives, but none achieve net-zero and many increase impacts like eutrophication, highlighting the need for product-specific assessments and more innovation to meet climate targets.[207] This underlines that producers must continually improve fermentation processes, e.g., use low-impact feedstock, renewable energy, efficient water use, to satisfy the EU's holistic sustainability criteria. In general, however, fermentation-based IA production aligns with Europe's regulatory trajectory, favoring low-carbon, low-waste technologies.

4.9.3. Incentives and subsidies affecting market entry and growth

The regulatory environment in Europe not only restricts harmful practices but also actively promotes sustainable industrial innovation. Companies aiming to produce or process IA in central and western Europe encounter a mix of incentives and penalties that shape market entry and growth:

- **Government Incentives & Funding**

European policy strongly supports the development and scaling of bio-based chemicals and advanced fermentation processes. The flagship initiative in this field is the Circular Bio-based Europe Joint Undertaking (CBE JU), a public-private partnership co-funded by the European Union and the Bio-based Industries Consortium.[77,122] The current CBE JU program (2021–2031) has a total budget of approximately €2 billion and dedicates annual calls exceeding €150 million for projects advancing biorefineries, bio-based chemicals, circular economy solutions, and demonstration plants.[225] CBE JU and its predecessor BBI JU funded more than 190 innovation projects, including numerous demonstrations of biorefineries across Europe. CBE JU awarded €197.5 million to 30 new projects across 33 countries to advance Europe's circular bio-based economy. Funding includes flagship biorefineries, scale-up of bio-based innovations, and research into new technologies, with projects targeting waste valorization and sustainable feedstocks, overall aiming to cut fossil dependency, boost rural jobs, and strengthen Europe's bioeconomy.[220] EU-wide innovation funding is also promoted through the Horizon Europe framework, which under Cluster 6 – Food, Bioeconomy, Natural Resources, Agriculture and Environment – has multiple calls for biotechnology, circular bioeconomy, and bio-based chemistry, providing grants for pilot projects and process improvements, such as optimizing fermentation yields or developing new bio-based polymers.[221]. The support tools include direct subsidies, low-interest loans, and R&D grants, which lower the barriers to entry and scale-up for innovative fermentation-based enterprises across Europe. The combined effect of EU and national programs promotes a competitive advantage for fermentation-derived products, such as IA, in the region by accelerating further bioprocess innovation, and expanding market uptake through coordinated funding und policy support. As an example, if the activities of a company are classified as sustainable (e.g., producing chemicals with 50% lower GHG emissions than the industry average, e.g., through utilizing circular feedstock), investors might be encouraged or required for certain portfolios to invest in those, which eases access to capital as a critical factor for growth. On the other hand, companies that do not adapt (e.g., sticking to high-emission, fossil-based processes) may face higher borrowing costs or difficulty attracting investment as financial institutions direct towards greener portfolios.

- **Market and Demand-Side Incentives**

The EU's regulatory ‘bans’, such as the regulation on restricting phosphates in laundry and dishwasher detergents,[200] create a market pull for safer, more sustainable alternatives. The shift away from phosphate-based detergents has accelerated the market adoption of alternative detergent builders, including bio-based and environmentally friendly chemicals, such as citrates and organically derived compounds, some of which are based on IA and other organic acids. These regulatory measures are examples of how policy can move markets toward greener products.[222] Beyond detergent formulation, policy focuses on comprehensive phosphorus management and stricter wastewater treatment practices, due to ongoing concerns over phosphates' contribution to eutrophication and water pollution. Success in reducing phosphorus pollution has depended in part on the widespread use of tertiary wastewater treatment plants, which can achieve very low phosphorus concentrations in effluent. However, restrictions on phosphate use in consumer products remain the key preventive method to control and decrease the overall phosphorus load in wastewater streams.[223] Suchlike measures shape the overall market environment to favor certain non-toxic, biobased materials, e.g. bio-based polymers, including those potentially derived from IA, and make them promising candidates for capturing new market segments seeking safer, sustainable alternatives. The EU’s Green Public Procurement (GPP) policies incentivize the adoption of sustainable products by encouraging public sector purchases that meet these environmental criteria, such as a bio-based content, overall reduced emissions, and non-toxicity. This provides a direct market advantage for companies offering bio-based polymers from IA, as these can help meet Green Public Procurement Criteria and Requirements[224] and thus gain preferential consideration in public. Consumer-facing regulations requiring the disclosure of product environmental footprints or recycled content also create market incentives. European consumers and brands increasingly favor bio-based, eco-friendly ingredients, boosting demand for sustainable products and making Europe an attractive market for launching new bio-based chemical products.[225,226] Overall, the regulatory landscape in the EU, illustrated by the phosphate restriction in detergents and reinforced by broader environmental policies and consumer preferences, creates strong market pull and incentives for bio-based chemicals like IA. Companies developing these greener alternatives stand to benefit from emerging market opportunities driven by sustainability-focused regulations and procurement policies.

- **Carbon Pricing and Emissions Costs**

From the opposite perspective on incentives, Europe’s carbon pricing mechanisms can act as a penalty for carbon-intensive processes. The EU Emissions Trading System (EU ETS), launched in 2005, is the EU’s main climate policy for cutting greenhouse gas emissions. It sets a cap on emissions and lets companies trade allowances, encouraging cost-effective reductions. Initially covering energy-intense large stationary industries, it expanded to aviation in 2012 and includes maritime transport from 2024. The system is designed to be cost-effective and economically efficient in achieving emission reductions.[227] Carbon taxes work best as part of a broader climate policy mix that combines price-based measures with subsidies, standards, and infrastructure investments to drive structural change toward climate neutrality.[241] Thus, avoiding carbon taxes can be a financial incentive for bioprocesses compared to carbon-emitting, e.g. petrochemical processes. As the EU forces climate policies (and aims to extend carbon pricing to more sectors), companies with low-carbon profiles will be at an advantage. Carbon pricing in 2024 covered about 23% of global greenhouse gas emissions at USD 32 per ton, up from 12% at USD 7 in 2014, and can trigger sectoral tipping points that drive rapid emissions reductions through technological adoption and fuel switching. When paired with redistributive measures at these tipping points, it is possible to cut emissions swiftly while sustaining economic growth and reducing inequality, offering a balanced path toward environmental and social sustainability.[228] Thus, in EU ETS countries, a USD 1 increase in expected future carbon prices leads to a 1.4% rise in low-carbon technology patenting. Firms adjust their price expectations gradually, and overall, higher carbon prices act as a strong driver for low-carbon innovation.[229]

- **Tax Credits and Subsidies**

Several European countries provide tax or financial incentives to support renewable and sustainable chemical production. These may include measures such as accelerated depreciation, investment tax credits for bio-based production equipment, or preferential corporate tax regimes for income derived from certain intellectual property known as patent box regimes.[230] While such schemes vary by country, they can create a more favorable investment environment for bio-innovation. At the EU level, state aid rules restrict direct subsidies to prevent market distortion, but exemptions exist for projects that advance environmental protection or innovation.[231] Such EU recommendations on tax incentives to accelerate the Clean Industrial Transition, aiming to support the Clean Industrial Deal (CID),[232] include allowing national governments and regional authorities to offer grants or tax advantages, for example, by helping to co-finance biorefineries or fermentation facilities in less economically developed regions, which can lower entry barriers and stimulate market growth.

4.10. SWOT analysis on the classical process for IA production

Having mapped the regulatory landscape for IA in Europe, the following section assesses its strategic position through a SWOT analysis of industrial-scale IA production, illustrating how these constraints shape strengths, expose weaknesses, enable opportunities, and define threats.

Strengths

Classical IA production is a submerged aerobic fermentation of sugars by *A. terreus* followed by crystallization. This process relies on a mature, well-characterized platform. Industrial practice and reviews consistently report robust performance, with routine titers above ~80 g L^{-1} from glucose and well-mapped parameters for optimization, notably pH control, aeration/mixing, and trace-metal management.[233–235] These variables have reproducible effects on IA rates and yields, giving operators validated methods at scale. Moreover, IA is formally recognized a “Top Value-Added Chemical from Biomass”[2] underlining its strategic relevance for bio-based polymers, coatings, dispersants, and related markets. Downstream, conventional concentration and crystallization is established, and a large body of work benchmarks alternative recovery options that can be grafted onto the classical flowsheet without redefining the upstream biology.

Building on this foundation, several advances further strengthen the classical pathway’s cost and scale outlook: (i) Cheaper substrates enabled by smarter media engineering, e.g., improvements in Inhibitor management allow for the production of IA from lignocellulosic hydrolysates or agricultural residues with considerable yields, lowering sugar OPEX exposure.[236] (ii) Process-intensified separations, e.g., adoptable extraction, adsorption, electrodialysis, and integrated in-situ product removal (ISPR) can enhance crystallization and reduce energy demand, improving the overall economics of the classical flowsheet,[67,237] and (iii) strain/host engineering beyond *A. terreus*, where engineered *Ustilago* spp. and other microorganisms achieve high yields at controlled low pH, offering routes to relax ion sensitivity and broaden substrate scope while remaining compatible with established unit operations.[238]

Weaknesses

The classical route has a narrow operating window and sensitivity to impurities. In particular, *A. terreus* IA synthesis collapses in the presence of trace Mn^{2+}, even tens of parts-per-billion can cut titers drastically, while interactions with phosphate and copper complicate control.[235,239,240] This makes low-impurity media and vigilant metals management mandatory, especially on crude feedstocks. The process is also highly oxygen-demanding: oxygen transfer and hydromechanical stress must be balanced carefully during scale-up.[234,241] Precise pH profiles are required to sustain production, increasing control intensity and acid/base usage.[233] Finally, lignocellulosic hydrolysates and molasses may introduce inhibitors and metals that reduce performance, and long, energy-intensive recovery methods (even with crystallization) remain significant cost contributors in techno-economic assessments.

Opportunities

Regulatory environment in the E.U., policy and sustainability engaging IA's "platform chemical" status, further supporting investments.

Threats

Economically, IA competes with entrenched petrochemical value chains, namely acrylic and methacrylic acid and derivatives. Despite structural fit and promising materials properties, fermentation costs, in particular costs for feedstock(s) and downstream processing,[68] still hinder broad displacement.[3,124,125] Therefore, the economic pressure from petrochemical-routes remains a persistent challenge. The industry footprint and supply are also relatively small and regionally concentrated in the Asia–Pacific area, which can limit resilience and bargaining power. In parallel, feedstock volatility and impurity risks directly impact yields and OPEX, and scale-up remains exposed to morphology/oxygen-transfer issues that can cap reactor productivity.[241]

4.11. Supply chain analysis (EU-focused)

In the upstream part of the supply chain, the key inputs are currently carbohydrate feedstocks such as glucose or other sugar-rich raw materials. The production route is biological, and therefore supply economics depend heavily on feedstock cost, fermentation performance, and downstream purification efficiency.[242,243] In the midstream production stage, IA is commercially made by submerged fermentation and then recovered through purification steps, which is similar to other bulk commodity acids. Therefore, and like for other organic acids yield, contamination control, and separation costs can affect supply reliability and final cost.[132]

For the EU market, the visible public supply base appears stronger on the distribution side than on the documented large-scale manufacturing side. European suppliers clearly market and stock IA for regional buyers, but there is no major EU-based production capacity. That suggests the EU market likely depends to an important degree on imported material and local distribution partners. This structure creates several supply chain risks for EU buyers. If Europe relies on imported products, buyers are exposed to freight delays, customs processing, inventory risk, and external production concentration. The European Commission's chemical trade guidance also shows that imported chemical products must meet EU market-access requirements, so logistics and compliance both matter in sourcing decisions. Moreover, the regulatory layer is important in Europe. Supplier information for the EU market states that IA falls under REACH registration requirements for EU supply, and ECHA maintains a substance information page for IA. This means compliance is not optional, but it is part of the supply chain itself, because non-compliant material cannot move easily into regulated EU applications. There is a specialty downstream opportunity in Europe. The Official Online Database for Cosmetics Ingredients in the EU (CosIng) lists IA as ingredient,[244] which indicates the usage in regulated personal care value chains, in addition to broader industrial uses described.[93] From a strategic view, the EU supply chain is supported by the region's interest in bio-based and circular economy chemicals. Public literature links IA to renewable chemistry and sustainable materials, which fits the broader EU policy direction. However, the commercial supply chain still faces practical limits from production cost, scale-up difficulty, and the need for reliable purification and logistics infrastructure.

4.12. Market opportunities

The main market opportunity for IA is in polymer and resin value chains where IA is used as a reactive building block (a co-monomer) to add acid functionality and tune performance, including in applications described in regulatory use information such as polymer-related uses.[245] A practical way to frame demand-side opportunity is "drop-in" or "near drop-in substitution" in formulations where IA can replace part of petro-based monomers, because IA is positioned in technical and public references as an established monomeric building block and is often discussed alongside alternative monomer options. The main restraint is that many downstream polymer markets are cost-driven, and IA demand can be sensitive to relative pricing, making a substitution only reasonable if IA offers clear performance benefits or a customer is willing to pay a premium for bio-based content. On the supply side, IA is an established industrial chemical with a mature compliance footprint in the EU (REACH registration).

4.13. Strategic recommendations

For an EU target, the most robust strategic path is to treat IA as an industrial chemical sold into regulated, specification-driven value chains, and to use EU compliance, customer qualification, and documented sustainability because IA has an EU REACH registration dossier and is used in industrial contexts.[246] To identify untapped market segments, EU polymer and formulation niches where IA's role as a reactive building block should be targeted. In practice, this strategy targets customers and segments that buy on specification, documentation, and technical service, and not only price, since substitution risk is a key constraint when alternatives are cheaper and performance differences are modest. A positioning towards a sustainable strategy can only be an addressable niche if this statement can be supported with credible documentation. Even though IA is produced by fermentation, which is framed as bio-based, sustainability outcomes depend on feedstock sourcing and energy, which affect the credibility claim in the EU market.

Strategic partnerships, or Mergers & Acquisitions (M&A) should be prioritized to create alliances with downstream formulators, resin producers, and distributors that provide technical service and access to regulated end markets, because IA's value is realized in polymer formulations and within industrial use chains where qualification and stewardship matter. Thus, strategic partnerships around joint development and qualification, e.g. through shared testing plans, agreed specifications, and supply commitments, are recommended, because long-term offtake and qualification reduce the volatility created by substitution and price pressure. For M&A, screening for targets that strengthen EU go-to-market execution, e.g., application labs, customer relationships in coatings, adhesives, or resins, should be targeted.

Market entry strategies, such as licensing, joint ventures, or in-house development, may be considered. If speed and lower technical risk are prioritized, entering the market via toll manufacturing or licensing with a fermentation operator should be considered, which enables focusing own investments on EU-grade purification, quality assurance and control, as well as documentation, since IA is commonly produced via fermentation and consistent quality and supply reliability are central to an industrial adoption.

In case of strong EU customer access, e.g., through an existing polymer or resin portfolio, but a lack of production on the other hand, a joint venture with an IA producer can align the economics around qualification and offtake, which is important because substitution risk can otherwise undermine volume stability. In-house development is desirable to build a defensible compliance-and-service platform in the EU, as EU REACH registration frames IA into a structured regulatory framework and downstream customers often require robust stewardship and consistent specifications from suppliers. Overall, reliability and compliance readiness are likely to be stronger differentiators than “novel chemistry”, because IA is already established with an EU REACH dossier and buyers in regulated chains often prioritize documentation, consistent specs, and supply continuity. A cost advantage should be pursued mainly through operational stability and commercial design, e.g., multi-year supply and offtake structures, since IA competes in markets where substitutions can occur when alternatives are cheaper.

4.14. Economic feasibility and financial outlook

The techno-economic work on IA production names feedstock and downstream processing (DSP) as major cost drivers and shows that the choice of purification route can shift the processing cost significantly. One downstream-focused TEA estimated upstream and fermentation processing costs at about 1.13 USD/kg, and then added route-dependent DSP costs (e.g., crystallization, adsorption, extraction, electrodialysis) ranging roughly from ~0.63 USD/kg to ~ 1.50USD/kg in that study’s scenarios, illustrating that purification selection can change total processing cost by close to a dollar per kilogram or more in the model.[68]

A separate process-design and scale-up study on IA from crude substrates reports that additional DSP steps such as decolorization may be needed to remove impurities, and that pH-adjusting agents can be used more heavily than in some process simulations, which implies higher chemical and waste-handling OPEX risk when moving from “clean” feedstocks to crude ones.[22] Because IA is most commonly discussed as a fermentation-derived product, cost structures are often framed around (i) feedstock (sugars or other carbon sources), (ii) fermentation performance (titer, rate, yield), and (iii) DSP complexity. These factors are explicitly treated as key cost levers in published bioprocess TEA tooling and studies.

4.14.1. Capital Expenditures (CAPEX) and Operating Expenses (OPEX)

CAPEX for IA production depends strongly on plant capacity and the process route (especially the downstream purification train). Capital cost generally rises with capacity, but the CAPEX per unit of annual capacity often decreases as plants get larger due to economies of scale (shared utilities, larger equipment sizes, and better fixed-cost spreading). At the same time, changing the process route can shift CAPEX significantly, e.g., fermentation-based IA requires fermenters and associated utilities. Likewise, the downstream can add different types and amounts of equipment and integration complexity, depending on the route, such as crystallization, adsorption, extraction, or electrodialysis. Overall, TEA literature highlights that purification choices mainly affect the overall economics and can require additional unit operations depending on broth quality and impurities, which in turn can increase both equipment count and supporting infrastructure needs.[22,68]

OPEX for IA production also cannot be expressed as one fixed value, because it depends on feedstock choice and price, fermentation performance (titer, rate, yield), and the downstream purification route. In the downstream TEA on IA from fermentation broth, the authors report an estimated upstream and fermentation processing cost of about 1.13 USD/kg, and then show that downstream processing adds an additional route-dependent cost (with different estimates for crystallization, adsorption, extraction, and electrodialysis-based options), illustrating that purification selection can shift total processing OPEX materially in the model.[68] In addition, process-design/scale-up work on using crude substrates for IA reports that extra downstream steps (such as decolorization) may be required to remove impurities and that pH-adjusting agent use can be higher than in simplified simulations, both of which imply potentially higher realized OPEX when moving from clean to crude feedstocks.[22]

4.14.2. Potential revenue streams and pricing strategy overview

Potential revenue streams for an IA project are typically tied to selling IA and/or selling formulated derivatives, for example, polymer-grade uses. IA pricing should be benchmarked against the closest substitute unsaturated (C-C double bond) monomers used by customers and then adjusted based on value-in-use, including performance and processing impacts in the end application. A price comparison among selected unsaturated monomers of similar technical properties and functionalities, e.g., acrylic acid, maleic anhydride, and fumaric acid, which can support relative positioning but should not be treated as a current market benchmark. Pricing decisions should also reflect the producer's cost structure, as techno-economic analysis indicates that downstream purification choices can materially affect IA processing costs and therefore pricing flexibility. In **Table 6,** IA is compared to selected unsaturated monomers of similar functionalities.

Table 6. Origin and price of IA, Acrylic acid, maleic anhydride, and fumaric acid.

Competing monomer	Typical origin	Competes with IA mainly as	Price, region, date
IA	Bio-based (fermentation)		2.2 – 2.6 USD/kg, Europe Q1, 2026
Acrylic acid	Petro-based (mostly)	Benchmark unsaturated monomer (substitute/alternative in polymers)	0.975 USD/kg, Germany January, 2026
Maleic anhydride	Petro-based	Unsaturated building block (resins, etc.)	1.23 USD/kg, Germany Decembre, 2025
Fumaric acid	Often petro-based, can be bio-based	Unsaturated diacid alternative in resins	1.3 – 1.6 USD/kg, Europe Q1, 2026

As shown in **Table 6**, IA is priced higher than the main petro-based benchmark monomers. In Europe in Q1 2026, IA at 2.2–2.6 USD/kg is roughly about 1.4–2.7 times the price of acrylic acid in Germany in January 2026 (0.975 USD/kg). It is also above maleic anhydride (1.23 USD/kg) and fumaric acid (1.3–1.6 USD/kg), which indicates that IA is currently positioned as a higher-priced specialty or bio-based option rather than a low-cost drop-in substitute. Therefore, substitution into applications dominated by acrylic acid, maleic anhydride, or fumaric acid is likely to require either clear performance advantages, regulatory/sustainability value recognition, or targeted niche segments where customers accept a higher monomer cost.

4.14.3. Profitability assessment, break-even analysis, and investment attractiveness

Based on a TEA study from 2019,[68] project profitability is highly sensitive to (i) the selected downstream processing (DSP) route and (ii) fermentation performance. This is because DSP can contribute approximately 0.6–1.5 USD/kg (in one set of TEA scenarios) in addition to upstream and fermentation processing costs, and this incremental cost can materially constrain gross margin when market prices are not substantially above production cost. From an operational perspective, the use of crude substrates may necessitate additional purification steps and higher consumption of pH-adjusting agents relative to simplified simulations, which increases uncertainty in realized OPEX and, consequently, uncertainty in break-even volume and payback period.[22] Therefore, investment attractiveness for an IA project is primarily a function of cost and execution risk rather than a single deterministic margin case.

4.15. Conclusion

IA remains a promising bio-based platform chemical. However, research indicates that the market is still relatively small and that recent growth has been more moderate than early forecasts suggested. The production remains concentrated in the Asia-Pacific region rather than in Europe. At present, broader market penetration is constrained by the continued cost advantage of established petrochemical substitutes such as acrylic acid, maleic anhydride, and fumaric acid. The analysis indicates that the most attractive opportunities lie not in high-volume commodity markets, but in value-added and specification-driven applications in which bio-based origin, regulatory alignment, and technical performance are commercially relevant.

Within the HemiCoat project, the most promising segments are IA-based coatings and surfactants, as these products correspond to application areas where substitution of fossil-based inputs is already being pursued. In addition, existing commercial examples support detergents, hygiene products, and selected personal care applications as relevant niche markets for IA-derived materials.

From a strategic perspective, the report supports prioritizing downstream, higher-value products rather than competing on commodity IA alone. It further indicates that successful market entry should be built around partnerships with formulators, (resin) producers, distributors, and application laboratories that can support qualification, technical service, and access to regulated end markets. The report also points to lower-risk commercialization models, including toll manufacturing, licensing, and joint ventures, alongside demonstration projects capable of validating performance and economic viability under industrial conditions.

Overall, the outlook for IA will depend less on its novelty than on the ability to deliver competitive and reliable execution. Feedstock costs, fermentation performance, downstream purification, compliance readiness, and credible sustainability documentation are the principal factors that will determine whether IA can progress from a niche bio-based intermediate to a broader industrial solution.

5. Alternative products derived from HC sugars

HC is also described as the second most abundant polysaccharide in lignocellulosic biomass after cellulose. HC sugars are the sugars released from the HC fraction of lignocellulosic biomass. This fraction is usually rich in pentoses, especially xylose and arabinose, although HC can also contain mannose, galactose, and glucose, depending on the biomass source,[247] thus representing a mixed sugar stream recovered from lignocellulosic biomass.[248,249] Because this stream can be directed either to selective products (by microbes or catalysts) or to energy recovery, HC sugars can be grouped into two processing routes: biological conversion, and chemical/catalytic conversion. Biological routes emphasize microbial products but can be sensitive to mixed sugars and inhibitors. Chemical routes emphasize catalytic conversion of pentoses to platform molecules such as furfural and to polyols such as xylitol.

5.1. Biological routes

The biological route uses microorganisms or isolated enzymes to convert HC sugars into fuels and other biobased chemicals under milder operating conditions than conventional chemical processing. This route is centered on the use of pentose sugars released from HC, especially xylose and arabinose, as substrates for microbial metabolism.

Ethanol

Xylose is a major sugar released from HC and has long been studied as a fermentation substrate for fuel ethanol production. Moreover, arabinose and xylose co-fermentation has also been engineered in recombinant strains. Naturally xylose-fermenting yeasts such as *Pichia stipitis*, *Pachysolen tannophilus*, and *Candida shehatae* have been reported to ferment xylose to ethanol, although there are industrial limits such as low ethanol tolerance, slow fermentation rates, and operational difficulty. A second strategy is metabolic engineering. Recombinant *Saccharomyces cerevisiae* strains expressing pentose pathways have been developed to ferment arabinose and xylose, which is important because industrial hydrolysates often contain mixed HC sugars rather than a single purified sugar.[248,250,251]

5.2. Chemical routes

The chemical route upgrades HC sugars through catalytic or acid-catalyzed reactions rather than microbial conversion. Furfural from pentose dehydration and xylitol from xylose hydrogenation or bioconversion are the main targets of this route.[247,249,252]

Furfural

Furfural is a major chemical product from HC sugars because pentoses such as xylose can be dehydrated to furfural. This makes furfural a green platform compound made from renewable biomass, and a product with broad downstream application potential.[252] The furfural route can start either from polymeric HC or from monomeric xylose, depending on whether hydrolysis and dehydration are carried out in separate or integrated steps. A deeper analysis of the production of Furfural from HC sugars is performed in the following chapter **5.3. Furfural: IA alternative derived from HC sugars.**

Xylitol (also in a biological route)

Xylitol is an important utilization route for HC sugars because it is produced from xylose, and xylose is the main pentose released from the xylan-rich fraction of HC.[247] In practice, the route involves pretreatment and hydrolysis of HC-rich biomass to generate a xylose-rich hydrolysate, followed by conversion of xylose to xylitol either through catalytic hydrogenation or through biotechnological methods in whole cells or with enzymes.[247,253] This pathway is commercially relevant because xylitol is already used as an alternative sweetener in food and pharmaceutical applications, which gives HC-derived xylose a clear value-added value. At the same time, the technical and economic performance of the route depends on several process factors, especially the yield of xylose from HC, the formation of inhibitory by-products during pretreatment, the efficiency of the conversion step, and the cost of downstream purification.[247,254]

5.3. Furfural: IA alternative derived from HC sugars

Furfural from HC sugars can be positioned as a downstream option for pentosan-rich side streams rather than as a stand-alone biomass route. It can be produced by direct conversion of HC-rich biomass, by conversion of isolated HC fractions or hydrolysates, or by dehydration of model pentose sugars such as D-xylose or D-Arabinose, but the route from HC sugars is especially relevant where pulping, or other biorefinery pretreatment processes (like organosolv) already generate aqueous HC streams. This matters commercially because HC can account for up to 35% of biomass and remains underused in many lignocellulosic value chains. Furfural is formed when HC is first hydrolyzed to pentose sugars and oligomers, mainly D-xylose and xylooligosaccharides, and these intermediates are then dehydrated under acidic or autocatalytic conditions. From a market perspective, this makes furfural a potential valorization route for already-separated HC liquors, which can improve overall biomass use in integrated production systems. The demand side supports interest in this route. Furfural has been commercial since 1921 and is linked to more than 80 chemicals and applications across plastics, pharmaceuticals, agrochemicals, solvents, and biofuels. The estimated global furfural market in 2022 was 365 kt, rising to nearly 500 kt by 2030, while European demand is expected to increase from 50 kt to 200 kt by 2030, and current European production capacity is only about 6.5 kt/a. In market terms, this points to an established end-use base and a possible regional supply gap if European production does not expand. The supply-side case for furfural from HC sugars is therefore not mainly about creating demand for a new molecule, but producing an existing molecule from better feedstocks and with better process economics. Conventional production still relies heavily on mineral acid treatment and steam stripping, uses around 16.2 tons of superheated steam per ton of furfural, and generates salt-containing waste streams after neutralization. Herein, the conventional furfural output is about 10.3 wt% relative to applied biomass, and up to 70% of the biomass can remain unused in the traditional pathway. These limits help explain why furfural production is concentrated in lower-cost regions, with China holding more than 70% of global capacity, followed by the Dominican Republic, South Africa, Europe, and India.[255]

The main market restraint is that production from real HC sugars is technically harder than production from clean model sugars. Aqueous HC fractions remain largely at the research stage because impurities and accompanying substances reduce yield and purity. A central issue is humin formation, which lowers furfural yield and can also create fouling and blockage problems, especially in continuous systems and with real hydrolysates rather than pure D-xylose feeds. This gap between model performance and real-feed performance is commercially important. In water-ethanol systems, ethanol has been shown to raise furfural yield from D-xylose from about 36–52 mol% up to as much as 90 mol% while reducing humin formation by about 60%. However, the same improvement does not transfer directly to real organosolv HC streams, where high ethanol contents can slow xylooligosaccharide hydrolysis and may even reduce furfural yield under some conditions, although humin formation still declines. In market terms, this means pilot or lab results based on simple sugars may overstate near-term commercial performance on real side streams. Among the production concepts studied for HC sugars, hydrothermal reactive distillation appears especially relevant from a market viewpoint because it addresses both yield and separation. In this approach, furfural is removed continuously through the vapor phase as it forms, which limits further degradation and polymerization. Herein, about 83 mol% furfural yield in the condensate, together with high purity and no detected residual sugars or humins in that condensate. This suggests that the strongest commercial opportunity may lie in process designs that combine conversion and *in situ* product removal for real HC-derived liquors rather than in simple batch dehydration alone.[255]

Overall, furfural from HC sugars is an established product with improving process options, not as an unproven end market. The commercial upside comes from integrating furfural production into lignocellulosic systems that already separate HC, while the main downside is that real hydrolysates still present yield, purity, and operability challenges. In practical terms, the route becomes more attractive when producers have access to pentosan-rich side streams, need additional value from HC, and can deploy process concepts that reduce humin formation and remove furfural quickly from the reaction medium.[255]

6. End products of HemiCoat: Biobased coatings and surfactants

6.1. Brief overview of biobased coatings and surfactants

Biobased coatings and surfactants are coating and surface-active ingredients made partly or fully from renewable biological feedstocks rather than fossil feedstocks. The European standard EN 16575 defines “bio-based” as derived from biomass, and the European Commission uses this standard in its bio-based product work.[256] In this analysis, the focus is on the EU market for IA derivatives used in coatings and surfactants. In coatings, IA derivatives are of great interest because the IA contains two carboxylic acid groups and a carbon-carbon double bond. Therefore, it can be used as a reactive building block in resins, UV-curable systems, latex binders, dispersants, and crosslinking chemistry. Both academic and patent literature describe itaconate esters, itaconic anhydride, and itaconate-containing polymers as candidates for coatings, adhesives, and related polymer systems.[1,39,125,257,258]

In surfactants and detergent ingredients, IA derivatives serve as polymeric itaconates and sulfonated itaconate esters. Polyitaconates can act as builders, dispersants, chelants, and anti-redeposition agents in cleaning formulations. Sulfoitaconate structures are being studied as anionic surfactants and as polymerisable surfactants, often called surfmers, which can become part of latex particles rather than remain as free surfactants.[258,259]

The EU market for IA-derived coatings and surfactants appears to be early-stage and specialty-driven. Publicly available sources show commercial products in detergent and cleaning additives, research and patent activity in coatings, and no transparent public EU market-size dataset for itaconic acid derivatives by coatings and surfactants end use.[114]

6.2. Demand and market trends

The demand is concentrated in uses where IA chemistry gives a clear formulation benefit. In detergent and cleaning formulations, polyitaconates are marketed as builders, chelants, dispersants, and water-conditioning polymers.[46,115] Moreover, the EU detergent market has a clear regulatory reason to value the biodegradability of surfactants, e.g., regulation (EC) No 648/2004 on detergents, which requires surfactants used in detergents to meet ultimate aerobic biodegradability criteria, subject to specified test methods and exemptions.[199] The EU has also restricted phosphorus in consumer laundry and dishwasher detergents in regulation (EU) No 259/2012, which amended the detergents regulation and limited the phosphorus content of consumer laundry detergents and consumer automatic dishwasher detergents.[200] The phosphorus restriction supports demand for non-phosphate builders and supporting polymers, but it does not by itself guarantee demand for alternatives, such as polyitaconates. However, this also means that polyitaconates must compete with other phosphate-free builder and dispersant systems such as citrates, carbonates, zeolites, polycarboxylates, and other polymers. An example of a successful business is Itaconix, which reports commercial sales into cleaning, hygiene, and beauty markets and positions its IA-based polymers as replacements for fossil-based polymers in selected formulations.[46,114] In coatings, demand is less established and only academic reviews describe IA as a renewable monomer for specialty polymers, resins, and coatings with excellent technical feasibility, but not a large-volume EU commercial adoption. Herein, a demand driver in coatings is the long-running reduction of volatile organic compound emissions. Directive 2004/42/EC limits volatile organic compounds (VOC) content in certain paints, varnishes, and vehicle refinishing products placed on the EU market.[260] Itaconate esters can be relevant to lower-VOC coating systems when they act as reactive ingredients that become part of the cured film rather than evaporating, and the regulatory advantage depends on the final formulation and must be demonstrated case by case.

Another demand driver is the EU policy emphasis on safer and more sustainable chemicals, and the European Commission's Chemicals Strategy for Sustainability sets a policy direction toward safer chemicals, substitution of substances of concern, and innovation in safe and sustainable chemicals. The Commission's SSbD framework encourages chemical and material developers to consider safety and environmental sustainability early in innovation.[261,262] For itaconate derivatives, the market case often depends on renewable carbon, biodegradation, and lower hazard claims, but the framework is voluntary and does not directly increase the demand in the market. Thus, the demand is restrained by cost and techno-economic studies identify feedstock cost, fermentation productivity, and downstream recovery as important cost drivers for IA production.[22,32,68] Overall, demand is restrained by competition from mature petrochemical monomers and polymers, such as acrylic acid, methacrylic acid, styrene, maleic anhydride, and related commodity chemicals, which are produced at much larger scales than IA and are historically embedded in coatings, adhesives, detergents, and dispersant markets. Demand is also restrained by qualification requirements, as coating and detergent formulators are required to fulfill many requirements, such as stability, compatibility, regulatory compliance, toxicology data, biodegradation data, performance data, and supply security before replacing established ingredients.[263] Therefore, the demand outlook is mixed, since regulatory and sustainability signals support interest, while cost, qualification burden, and limited public evidence of large EU supply restrain fast adoption.

6.3. Supply and production trends

Public evidence from company reports, EU project databases, academic reviews, and supplier information does not indicate an EU-27-based, commodity-scale plant for the production of IA or IA derivatives dedicated to coatings and surfactants. The public record instead points to a market served by non-EU or historical producers, specialty derivative companies, distributors, EU research projects, and application-development work. Itaconix, which headquarter is based in London, UK and whose production site is listed in Stratham, US, is a relevant producer of IA-based polymers for cleaning and related markets. The company reports commercial products based on

IA chemistry and serves cleaning, hygiene, and beauty applications, but its public reports do not disclose EU-only production capacity for coatings and surfactants.[114]

IA derivatives can be produced from the monomer through established chemical transformations. Esterification can produce dialkyl itaconates such as dimethyl itaconate, diethyl itaconate, and dibutyl itaconate. Dehydration can produce itaconic anhydride. Polymerisation can produce polyitaconic acid, salts, or copolymers.[37,124,125] Sulfonated itaconate esters have been described in scientific literature as anionic surfactants. However, these compounds are not represented as large-volume EU surfactants, but might be emerging or specialty candidates rather than proven commodity surfactants. EU research activity has included work on bio-based coatings and bio-based chemical building blocks. EU-funded projects, as listed in the CORDIS records, show EU-funded collaborations in the broader field of bio-based chemicals and coatings. However, project activity does not demonstrate commercial capacity, and project results do not always translate into industrial applications.

Supply-chain maturity differs by derivative. Simple itaconate esters and IA salts appear to be available through standard specialty-chemical and laboratory-supply channels, suggesting a more established supply route than other (newer) itaconate surfactants. Simple esters such as dimethyl itaconate and diethyl itaconate are listed in chemical databases and supplier catalogues, including PubChem, TCI Deutschland, Sigma-Aldrich, and ChemicalBook. This supports the view that these esters are accessible through standard specialty-chemical channels, although catalogue availability does not prove large industrial volume or EU coatings-market adoption. Likewise, dimethyl itaconate also has an ECHA registration dossier, being a recognized substance in the EU chemicals system. However, this does not translate to the EU demand, but it supports higher supply-chain maturity than a purely experimental molecule. IA is also listed by suppliers and distributors, including European-facing suppliers, and supplier descriptions identify IA as a raw material for dialkyl itaconates, polyitaconates, resins, latexes, detergent builders, and scale inhibitors, and therefore is an upstream monomer, which is accessible through specialty supply channels.[30,37,60,115,124,125,127,245,259]

Polyitaconates have clearer commercial evidence, as Itaconix markets products are based on polyitaconates to produce odor neutralizers and multifunctional chelants. Its DSP 2K product is described as a 100% plant-based multifunctional chelant, consisting of a low molecular weight linear polyitaconic acid partially neutralized with sodium salt.[46] More examples of Itaconix products are listed in **Table** 3.

6.4. Competitive landscape

IA-derived ingredients and building blocks are primary used in (A) coatings, e.g., binders, or dispersants relevant to paints, coatings, adhesives) and (B) surfactant-adjacent applications, e.g., polymeric dispersants, chelants, scale inhibitors used in formulated products such as detergents and water solutions. Therefore, this analysis distinguishes three competitive layers:

(i) Upstream IA producers, such as fermentation-based commodities. (Discussed in section 4.2.)

(ii) Downstream derivative or material innovators that use polyitaconic acid, or salts to design specialty polymers positioned into formulations.

(iii) Existing petro-based alternatives that compete at the performance or at price level, e.g., acrylic-based dispersant polymers, conventional surfactants, and functional polymers.

The competitive landscape for IA-derived coatings and surfactant-adjacent formulated products is best analysed in an upstream-to-downstream chain in which feedstock availability and qualification are as decisive as technical performance. Upstream, the IA supply base includes multiple producers, particularly in Asia, competing primarily on capacity, consistency, and cost. These producers provide the foundation for downstream derivatives and polymers.[93]

Downstream, specialists compete by translating IA into differentiated monomers and polymeric ingredients that can be adopted by formulators. Herein, Itaconix is one of the most visible examples of this approach, describing a commercial launch of plant-based products for paints, coatings, and adhesives positioned as plant-based building blocks, and presenting a broader portfolio of IA-based ingredients across applications consistent with a strategy focused on selling functional ingredients rather than commodity acid alone. In practice, these downstream offerings compete less against other itaconate players and more against established petro-based ingredients that are already present in the market. For coatings, many of the functional roles targeted by IA-derived polymers, such as dispersant or binder roles, are already mature, and widely covered by petro-based formulations, providing well-qualified alternatives from a wide range of suppliers. In surfactant-adjacent applications, including detergents and water-solution formulations, incumbent systems are deeply established, and competition is typically shaped by tight pricing and clear, standardized performance targets. As a result, competitive success is typically determined less by whether an ingredient is bio-based and more by whether it can demonstrate drop-in performance, dependable supply, and attractive total cost of ownership. Barriers to entry and competitive advantage build up at several points along the value chain. Upstream, cost and reliability depend heavily on how efficiently producers can run fermentation and how effectively they can purify the product. The fact that there are multiple established producers suggests upstream competition is strong and is driven mainly by scale, manufacturing cost, and consistent quality.[93] Downstream, the main defenses are about turning IA (derivates) into ingredients that work in formulations. Herein, an advantage comes from application-specific derivative(s) and polymer design, practical formulation know-how, especially how an ingredient behaves in different systems, and technical service that helps customers test, optimize, and qualify new ingredients. This support matters because customers often face long validation and approval cycles for coatings and other formulated products, and they want to minimize the risk of switching away from familiar incumbent solutions.

Overall, the market has a split structure. There are many upstream commodity suppliers, but downstream sales into coatings and formulated products appear to be driven by fewer specialists with clear product stories and differentiated positioning. Herein, downstream players need to show that IA-derived ingredients can match or beat the performance of established alternatives and that they can be supplied reliably at an industrial scale, while upstream producers focus on making the feedstock cost-effective, consistent, and dependable over time.

6.5. Pricing and cost factors

Bio-based coatings pricing is shaped less by a “green premium” than by how the full formulation competes regarding performance and total cost. On the cost side, the largest driver is typically raw materials, e.g., bio-based binders, monomers, and functional additives, which can be more expensive than petro-based equivalents because they are often produced at a smaller scale, may require additional purification or stabilization steps, and may have a narrower pool of qualified suppliers. Where bio-based routes depend on agricultural inputs, feedstock availability and seasonality can also influence input costs, which then flow into resin and additive pricing.[264]

Manufacturing economics adds another layer, as costs are sensitive to plant scale and utilization, process yields, and the complexity of downstream processing, e.g., separation and purification requirements. Likewise, energy and utilities are economically relevant in producing the coating components and in curing the final coating system. In practice, buyers frequently evaluate coatings on cost-in-use rather than only price per kilogram. Coverage rate, solids content, drying time, and cure requirements influence labor, throughput, and energy use, while durability and maintenance intervals affect lifecycle cost and warranty risk. A bio-based coating that improves productivity, such as one with fewer coats, faster line speed, or extending service life, can justify a higher unit price, whereas a product that requires extra formulation work or compromises performance will face strong resistance even if it offers sustainability benefits.[265]

Formulation-level impacts can be decisive. Switching to a new bio-based resin or functional ingredient can force changes in the additive package, including dispersants, wetting agents, defoamers, rheology modifiers, or coalescing agents. Moreover, it may affect pigment dispersion behavior and storage stability, which can raise development costs. Those reformulation and qualification efforts are economic barriers, because coatings customers often require extended testing regarding appearance, compatibility, adhesion, weathering, or stability. The time and cost of that validation effectively become part of the "price" of adopting a new bio-based input. Regulatory and sustainability requirements can both increase and reshape costs. Complying with VOC limits and hazard labeling constraints can restrict usable raw materials and drive additional testing. Separately, the cost of substantiating sustainability claims, such as documenting bio-based content or building product carbon footprint or entire LCA datasets, adds overhead. However, it may also allow a preferred supplier status or modest pricing power.[266]

6.6. Regulations, standards, and environmental considerations

Europe's regulatory environment is a defining factor in the market outlook for biobased coatings, because compliance requirements shape product design, time-to-market, and customer adoption as much as performance and price. REACH is the main EU chemicals framework that affects IA derivatives. Under REACH, manufacturers and importers have obligations linked to registration, safe use, and communication through the supply chain, depending on substance identity and tonnage.[183,267] Moreover, the EU's Classification, Labelling and Packaging (CLP) Regulation sets mandatory rules for how chemical substances and mixtures, including biobased binders, solvents, and additives, must be classified and labelled before they can be placed on the EU market. This means that any coatings must undergo hazard assessment and, where relevant, carry standardized hazard pictograms, statements, and compliant packaging, which can influence buyer perception and downstream handling requirements. As a result, companies competing in Europe must treat CLP compliance as a core market access requirement and a potential differentiator, since formulations that achieve targeted performance while reducing hazard classification can face fewer commercialization frictions and broader acceptance across industrial and consumer segments.[184]

For surfactants used in laundry detergents, Europe's regulatory framework is a decisive market gatekeeper: Regulation (EC) No 648/2004 (the Detergents Regulation) requires surfactants used in detergents placed on the EU market to meet ultimate aerobic biodegradability criteria. This requirement is directly relevant to itaconate-based surfactants, because if they are marketed in the EU as surfactants for detergent applications, they must demonstrate compliance with these biodegradability standards, which can influence product positioning, testing costs, and speed of market entry. For detergent builders and polymers, biodegradation and overall environmental fate remain commercially important in Europe, even where the legal requirements are not identical to those applied to surfactants. This is because these ingredients are designed for high-volume use and can enter wastewater streams and, ultimately, aquatic environments after consumers or industrial users discharge wash water, making their persistence and downstream impacts a key factor in customer requirements, retailer standards, and product acceptance.[199,200,222]

For coatings, Europe's VOC regulation is a central market constraint, because it directly influences formulation choices and the viability of new chemistries. In particular, Directive 2004/42/EC sets VOC content limits for certain decorative paints and varnishes as well as vehicle refinishing products placed on the EU market. Reactive itaconate-based ingredients can support compliance and improve marketability only when they genuinely reduce VOCs, for example, by replacing a volatile solvent or non-reactive diluent and chemically incorporating into the cured coating film, rather than evaporating during application and drying.[260]

Europe's voluntary ecolabelling framework can shape demand in both coatings and detergents by influencing brand positioning, retailer acceptance, and public procurement criteria. For paints and varnishes, the EU Ecolabel for indoor and outdoor paints and varnishes includes requirements related to hazardous substances, VOCs, performance, and consumer information, which can encourage the adoption of lower-hazard, lower-emission ingredient options, even though it does not specifically require IA derivatives. In parallel, the EU Ecolabel for hard surface cleaning products, laundry detergents, and related product groups sets product-specific criteria linked to aquatic toxicity, biodegradability, dosage efficiency, packaging, and restricted substances, supporting market interest in biodegradable and lower-impact surfactant systems; however, eligibility depends on how each ingredient performs under the relevant group's detailed rules and thresholds.[216,231]

Bio-based content, e.g., in coatings, is not proof of a lower environmental impact, and this is increasingly becoming important for market credibility, customer acceptance, and regulatory-risk management. The European Commission's bio-based product support and its broader sustainability policy focus emphasize that renewable feedstock and "bio-based" claims should be substantiated through appropriate standards, life‑cycle thinking, and transparent, credible datasets. In practice, this pushes suppliers toward LCA, because fermentation-based chemicals can carry impacts across the value chain, ranging from feedstock cultivation, fertilizer inputs, and land-use effects to energy and water demand, auxiliary processing chemicals, purification intensity, or transport. As a result, each IA derivative needs a product- and application-specific environmental assessment and, ideally, third-party verification before broad sustainability claims are made, particularly in markets where buyers compare alternatives using standardized sustainability matrices. In parallel, the European Commission's SSbD approach is relevant for new IA derivatives because it links safety, functionality, and sustainability considerations early in innovation, including hazard profile, exposure potential, and life‑cycle impacts. Suppliers that use SSbD to document lower hazard classifications, reduced emissions, or improved life‑cycle performance may gain a competitive advantage in procurement-driven segments. However, SSbD remains a recommendation rather than an explicit compliance requirement.[261]

The environmental position of polyitaconates is application-specific, because the relevant impact drivers depend on how the material is used and released. In detergents, a polymer used as a functional ingredient should be assessed against criteria that reflect real-world discharge pathways, including biodegradation, aquatic toxicity, fate in wastewater treatment and receiving waters, and the effective dose, since even a "greener" polymer can have a different footprint if higher treat rates are needed to achieve similar performances. The environmental evaluation of itaconate "surfmers" is likewise application dependent. While a surfactant from monomers that becomes covalently bound into a latex particle could reduce free-surfactant levels and subsequent migration or leaching, this advantage must be demonstrated for the specific polymer chemistry, formulation, and end-use conditions, including any residual unreacted species and the stability of the bound functionality over the product's life cycle.[1,199,259]

6.7. Outlook and scenarios

The EU market for IA derivatives in coatings and surfactants appears to be in an early, specialty-led adoption phase, supported more by targeted commercial positioning and ongoing technical development than by a broad, commodity-scale conversion. However, there are selective use cases, especially in cleaning-related polymers, but no widespread substitution of petrochemical platforms across EU coatings and surfactant industries.[37,81,114] Near-term momentum is clearest in polyitaconates, where supplier materials and company reporting provide the most evidence of commercialization in sectors such as home care or detergent-adjacent applications. Therefore, polyitaconates look like the current market anchor in terms of demonstrated positioning and product develpoment.[112,114,115] In contrast, itaconate esters and itaconic anhydride show strong technical relevance for coatings, e.g., as building blocks and functional intermediates. However, at the time of this report, data is weighted toward research, patents, and specialty availability rather than toward high-volume coating adoption. Therefore, coatings-related demand concentrates in niche formulations, development programs, or specific performance-driven uses, rather than large-scale replacement of currently used monomers and additives.[37,81,124–127] For sulfoitaconate surfactants and itaconate "surfmers", the outlook is promising but comparatively less commercially mature. Neither concepts nor synthesis routes demonstrate large EU market penetration or broad adoption by major detergent and surfactant value chains.[1,259] Across these routes, competitive differentiation is likely to hinge on a three-way trade-off:

1. Delivered formulation performance (cleaning efficacy, coating durability, compatibility)
2. Cost and qualification economics (delivered cost-in-use, supply assurance, reformulation effort)
3. Credible sustainability and compliance value (renewable carbon, biodegradability, VOC and hazard profile, ecolabel and procurement alignment)

Policy direction in the EU continues to favor safer and more sustainable chemicals, which supports the continued development and pull-through demand for renewable and lower-hazard alternatives. However, this does not translate into a rapid market conversion, particularly in cost-sensitive, performance-critical coatings and surfactant systems. Overall, the outlook is cautious growth, because itaconate chemistry shows functional fit and policy alignment, but no rapid, broad EU penetration in coatings and surfactants at this stage.[82,114,198]

Scenarios

In a **base (gradual) scenario**, adoption expands first in detergent additives, specialty cleaning products, and selected coatings use cases, rather than through rapid, broad substitution across EU coatings and surfactant markets. This scenario is supported by the relatively stronger public commercial evidence for polymeric itaconate solutions in cleaning-adjacent applications, while scale-up, qualification timelines, and delivered cost competitiveness continue to constrain faster conversion, even as EU policy direction and customer sustainability preferences improve the value proposition in specific formulations.

A **more accelerated uptake scenario** would require clear validation by major formulators at an industrial scale, alongside more secure EU supply and stronger compliance that explicitly rewards renewable carbon, biodegradability, lower VOCs, and improved hazard profiles.

Because public evidence does not yet indicate broad EU commercial conversion in coatings and surfactants, this scenario would likely be accompanied by visible market signals such as large product launches, multi-year supply agreements, and credible commitments to scale. VOC and detergents regulation provides a plausible mechanism for compliance-driven adoption where IA derivatives can meet performance requirements.

In a **downside (persistent niche) scenario**, adoption remains limited to specialty positions if petrochemical producers maintain a durable cost advantage, if performance benefits are insufficient to justify reformulation and qualification, or if competing (non-IA) bio-based platforms scale more quickly and capture sustainability-driven demand. This scenario is consistent with the current public evidence gap in EU capacity, pricing, and large-volume end-use adoption, and with the sensitivity of fermentation economics to process conditions and downstream recovery efficiency.[114,156,198,199,260]

Key uncertainties

One primary uncertainty is EU production scale and supply visibility, and public sources do not provide a clear EU27 capacity base for IA derivatives used in coatings and surfactants. Evidence of a shift would include announced EU fermentation capacity, disclosed commercial capacity for relevant derivative grades, or public offtake agreements that demonstrate secure, repeatable supply.[114]

A second uncertainty is cost reduction and production economics. IA and derivative competitiveness remain highly sensitive to feedstock cost, yield, productivity, downstream recovery and purification efficiency, as well as scale. Evidence that would improve the outlook includes higher-yield strains, lower-cost or more resilient feedstock strategies, improved purification processes, and integrated production approaches that reduce energy intensity and delivered cost.[156]

A third uncertainty is feedstock sustainability, as sugar-based fermentation can raise questions about land use and food or feed competition, which can weaken procurement and ecolabel value. Evidence of a stronger outlook would include certified sustainable inputs, greater use of residue-based or lignocellulosic sugars, such as in the HemiCoat project, and transparent LCAs that remain credible under third-party scrutiny.

A fourth uncertainty is the technical performance in coatings, particularly long-term durability in formulations. Itaconate derivatives must meet application-specific requirements across adhesion, hardness, flexibility, gloss, weathering, chemical and water resistance, pigment compatibility, and storage stability. Evidence that would change the outlook includes repeatable third-party test data and commercial coating launches supported by long-term field or accelerated weathering results, in a context where ecolabel criteria are increasingly relevant for market access and specification.[44,116,129]

A fifth uncertainty is surfactant and detergent performance and compliance, including biodegradation and aquatic safety, alongside cleaning performance. For broader adoption, IA-based surfactants and polymers must demonstrate hard-water tolerance, foam control or foam stability, formulation compatibility, and compliance with detergents and ecolabel expectations. Evidence of a shift would include product registrations, disclosed use in ecolabel-compliant formulations, and confirmed adoption by large detergent producers.[199,200]

A sixth uncertainty is regulatory changes and specification shifts. EU chemicals policy is moving toward safer and more sustainable chemicals, but the implications will differ by substance class and application. The outlook could change materially if binding rules emerge on polymer biodegradation, VOC limits tighten further, incumbent additives face restrictions, or procurement rules become more explicitly reward renewable carbon and lower hazard profiles.[82,198]

A seventh uncertainty is competitive pressure from other bio-based platforms. Alternatives such as (alkyl) polyglycosides, biosurfactants, lactic and succinic derivatives, and bio-based acrylic routes may meet the same sustainability-driven demand with faster scale-up or better cost-performance. Evidence that would weaken the IA outlook includes faster commercialization, lower delivered cost, or stronger performance from competing renewable platforms in key formulation niches.

An eighth uncertainty is customer willingness to pay and repeatability of demand. Coatings and cleaning markets are often cost-sensitive, and therefore, bio-based ingredients need a clear performance, compliance, or credible sustainability advantage that supports purchasing. Evidence of a stronger outlook would include repeat orders, long-term supply contracts, and commercial launches that explicitly position IA chemistry as a material value driver rather than a minor “green” additive.[114]

A ninth uncertainty is data transparency and market measurability. Public sources rarely isolate EU demand for IA derivatives across binders, dispersants, reactive diluents, and surfactants, which limits the ability to size the market and track adoption. Confidence would improve with trade data mapped to derivative categories, disclosed capacity by grade, audited sales by application, or recognized market datasets with transparent methodology. [114]

7. End product of HemiCoat: Biobased adhesives for wood

7.1. Brief overview of biobased adhesives and their key uses

Biobased adhesives are adhesive systems made in whole or in significant part from biological feedstocks such as lignin, tannin, starch, and plant proteins. In the wood sector, they are mainly examined as alternatives or partial substitutes for conventional amino and phenolic resin systems used in wood-based panels and related products. Currently, the wood panel industry continues to rely primarily on petroleum-derived thermosetting adhesive systems formed through reactions of formaldehyde with urea, melamine, and phenol. These resin systems are of comparatively low cost, and their properties can be tailored to specific panel types and manufacturing conditions. Bio-based adhesive alternatives have found it difficult to enter mainstream panel production, mainly because they must meet strict cost and performance requirements, but also, moisture tolerance and mechanical strength remain persistent challenges.[268,269] However, formaldehyde emissions are the most immediate driver for change in wood panel adhesive systems, outweighing sustainability arguments alone in current decision-making. It notes that both regulatory limits and voluntary requirements have become more stringent over time, increasing pressure to reduce emissions. As examples of this regulatory momentum, formaldehyde has been reclassified as a known human carcinogen, and there are limits for formaldehyde emissions from composite wood products.[268]

The current market situation is mixed. Soy-based systems have already reached commercial use in plywood, and recent sources also state that soy-based adhesives are commercially applied in plywood and particleboard manufacturing. By contrast, tannin-, starch-, and lignin-based systems generally have limited industrial applications, despite substantial research and development activity. However, biobased wood adhesives have progressed beyond purely laboratory-stage development, but commercial applications apart from soy-based solutions remain limited.[257,268–271] Despite intensive research efforts, a significant performance gap still persists between many bio-based adhesives and their petroleum-based counterparts. Several barriers to broader industrial adoption have been identified, including weak adhesion in starch-based systems, reduced water resistance in lignin- and protein-based formulations, and the inherent water sensitivity of many proteins. Tannins may mitigate some common shortcomings of other biobased approaches mentioned above, but are limited in availability. Overall, bio-based wood adhesives continue to require targeted formulation development, which remains necessary rather than optional.[257,269,270] Another restraint is that several promising systems are presently better suited to interior or non-structural applications, e.g., biobased lignin-glyoxal adhesives for interior plywood applications.[272]

7.2. Demand and market trends

Concern about formaldehyde emissions from conventional wood panel adhesives is the major factor behind the current push toward bio-adhesive development of wood-based composite panels. Moreover, a broader awareness of environmental sustainability and doubts about the long-term security of petrochemical supply is gaining weight as important reasons for the growing interest in biobased wood adhesives.[269,270]

Although adhesive demand cannot be inferred directly from wood-based panel production, it is possible to estimate adhesives for wood-based panels based on the scale and trend of the panel segment production in which wood adhesives are used. After a decline of more than 6 % in 2023, wood-based panel production in Europe slightly increased by 1.9% to a total of 57.4 million m^3 in 2024.[273] Therefore, demand for bio-and petro-based wood adhesives and binders is estimated at USD 20.7 bn in 2025, with the predicted annual growth rate of 4.0% until 2035.[274]

7.3. Supply, production trends, and major producers

Commercial production is strongest where biobased adhesives can use existing agricultural or forest-industry streams and be dropped into established panel or plywood manufacturing lines with minimal process changes. Herein, soy-based systems are the most established commercial route, while tannin-, starch-, and lignin-based systems remain less broadly industrialized overall.[268,270]

In North America, the most visible named supply chain is soy-based plywood. Herein, Solenis's Soyad adhesive technology provides a formaldehyde-free soy adhesive system used for hardwood plywood, particleboard, medium-density fibreboard (MDF), and engineered wood flooring, with more than 150 m hardwood plywood panels being produced globally, demonstrating a production that has moved beyond a single niche end use.[275,276] Another company in this sector is Columbia Forest Products, a downstream panel producer linked to the soy route. Its PureBond soy-based hardwood plywood technology has been in place since 2006, and more than 200 m panels have been manufactured and placed in service.[277] These routes and similar North American chains demonstrate the full commercial pathway from an agricultural raw material to adhesive formulation and finally finished plywood output.

Europe shows a different supply model centered on forest-industry side streams, especially lignin. Lignin is a byproduct of the pulp industry and, therefore, it is produced in millions of tons across Europe, which gives lignin-based adhesives a potential scale advantage over biomaterials that require a new collection and processing chain. Stora Enso is scaling kraft-lignin binders to replace fossil-based phenols in plywood and wood-panel adhesives, leveraging its large pulp-side feedstock. In Europe this is progressing through partnerships with panel makers, with Lineo® replacing about 40% of fossil glue and NeoLigno® already produced at industrial scale with performance comparable to conventional binders.[278–282]

Compared with soy and lignin, tannin and starch supply chains appear less standardized and less visible. Industrial applications of tannin- and starch-based panel adhesives are limited, driven more by formulation issues than by broad commercialization. Nevertheless, tannin-based adhesives are suitable for industrial wood-panel production conditions. A paper published in 2012 reported nine years of industrial production and trials in Chile using pine tannin extract to manufacture both particleboard and MDF. Herein, tannin-based adhesives could be used on different types of factory equipment, including an older multi-daylight particleboard line and a more modern single-daylight MDF line. Thus, tannin-based systems are compatible with existing manufacturing infrastructure and do not require entirely new production platforms. In performance terms, pine tannin adhesives produce panels of good quality at reasonable cost and with low formaldehyde emissions.[283]

7.4. Competitive landscape

Research on bio-based adhesives for engineered wood products has grown rapidly as the industry seeks alternatives to petroleum-based resins such as Phenol-formaldehyde (PF), Urea-formaldehyde (UF), Melamine-formaldehyde (MF), or polymeric diphenyl methane diisocyanate (pMDI), with a focus on three main renewable feedstocks: lignin, starch, and plant proteins. These materials are suitable for wood composites, but their performance often depends on chemical modification or blending to improve key properties such as reactivity, water resistance, curing behavior, and bonding strength. Lignin is promising as a partial phenol substitute or as part of formaldehyde-free systems, while starch is attractive because of its low cost and availability, but usually requires modifications to improve water resistance and storage stability.[284]

The competitive landscape is still narrow and chemistry-specific rather than broad and consolidated. The clearest commercial positions are soy-based systems in North American plywood and lignin-based systems in European plywood, board, and building-material applications, while tannin-based adhesives appear more fragmented and less clearly mapped to large current branded suppliers.[268,270] **Table 7** lists the main segments for biobased wood adhesives, their main producers, and the competitive position.

Table 7. Soy-, lignin-, and tannin-based binders and adhesives with their main producers and competitive positions.

Segment	Company (product)	Competitive position
Soy-based plywood and panels	Solenis (Soyad), Columbia Forest Products (PureBond)	Strongest documented commercial track record in hardwood plywood, which is positioned around no-added-formaldehyde or formaldehyde-free performance and compatibility with mainstream panel production
Lignin-based binders	Stora Enso (Lineo, NeoLigno)	Strongest visible lignin platform that competes on pulp-side feedstock access, industrial scale, and reduced fossil/formaldehyde/isocyanate content
Lignin-based downstream adopters	Paged, Latvijas Finieris, Koskisen, Moelven, IsoTimber	Compete by bringing bio-based binders into specific plywood, furniture-board, and structural-board products, but not selling merchant adhesives

Segment	Company (product)	Competitive position
Tannin-based adhesives	No multinational branded leader	Industrial history exists, but current competition appears more niche, formulation-led, and less standardized at company levels

Soy-based systems have the strongest documented commercial impact, also because soy protein was among the first bio-based adhesives launched commercially for plywood manufacturing, as demonstrated by Solenis's Soyad adhesive technology (see previous chapter 3.6.3. Supply, production trends, and major producers).[275,276] Another product is PurePond by Columbia, which has been in place since 2006, and more than 200 million panels have been manufactured and placed in service.[277] This gives Solenis and Columbia a defensible position based on commercial history, installed production, and a product story around formaldehyde-free or no-added-formaldehyde plywood.

Lignin is a pulp-industry side stream that is produced in millions of tons across Europe, which gives it an upstream advantage compared to soy- or tannin-based adhesives. Overall, lignin-based competition appears stronger in Europe, where NeoLigno (Stora Enso) is offered at an industrial scale and can be supplied across the region.[278] Stora Enso's competitive model appears partnership-based with downstream applications, with Paged and Latvijas Finieris in lignin-based plywood development, Koskisen in furniture boards, and Moelven and IsoTimber in structural boards and building elements.[279–281]

Some downstream wood-product producers are also building their own competitive identity around bio-based adhesive adoption. Latvijas Finieris, a leading Latvian birch plywood manufacturer, has begun construction of a first-of-its-kind natural resin factory in Riga's Bolderāja neighbourhood. The facility will produce eco-friendly synthetic resin from lignin as a greener substitute for fossil-based phenol. With a planned capacity of 45,000 tons per year and a total investment of around €40 million, the factory is expected to be completed by spring 2026 and is part of the EU Horizon 2020-funded VIOBOND research consortium. This initiative builds on the company's already-established "Riga ECOlogical" product line, which has been using lignin-based adhesive in its Riga Wood birch plywood for several years. The eco-friendly glue retains all the technical properties of conventional plywood while reducing carbon footprint, and formaldehyde emissions. This factory will allow Latvijas Finieris to scale this technology to an industrial level.[285,286] Koskisen has developed the world's first 100% wood-based furniture board, called Zero Furniture Board. Unlike traditional furniture boards that rely on fossil-based adhesives and plastics, this innovative product uses only wood-derived materials, including a bio-based binder, making it fully sustainable and circular. It is designed as a drop-in replacement for conventional furniture boards, offering comparable performance while significantly reducing the environmental footprint of furniture manufacturing.[282]

Overall, the main competitive factors in biobased wood adhesives are:

- access to scalable feedstock streams such as soy supply or pulp-derived lignin
- compatibility with existing panel manufacturing equipment
- emissions and safety positioning around formaldehyde-free or low-emission performance
- if the product can compete as a partial drop-in replacement rather than requiring a full process redesign

7.5. Regulations, standards, environmental considerations, and cost factors

Regulation and standards are central to the wood adhesive market because wood adhesives are closely linked to panel emissions and product compliance. The main regulatory implication for biobased wood adhesives is that EU policy now targets the formaldehyde emission performance of finished bonded products, especially furniture and wood-based articles, rather than only the chemistry of the adhesive itself. Regulation (EU) 2023/1464 adds a REACH Annex XVII restriction stating that, after 6 August 2026, articles cannot be placed on the market if formaldehyde released under the specified test conditions exceeds 0.062 mg/m^3 for furniture and wood-based articles or 0.080 mg/m^3 for other articles. Moreover, it defines the 6 August 2027 date for a formaldehyde interior limit in road vehicles. The regulation explicitly identifies wood-based panels, articles made from them, other wood-based articles, and furniture containing wood or other materials made with added formaldehyde as major indoor emission sources. The Commission justifies a lower limit because these product groups are among the largest contributors to indoor formaldehyde exposure. Annex XV restriction dossier found that risks to human health from formaldehyde released from consumer articles in indoor environments are not adequately controlled and that Union-wide action is needed. The Commission further concluded that there is an unacceptable risk from formaldehyde released from articles and that an emission-limit restriction is the most appropriate EU-wide measure to reduce inhalation exposure of the general public indoors. The new restriction does not apply to articles where formaldehyde or formaldehyde-releasing substances are exclusively naturally present in the materials, articles exclusively for outdoor use, certain industrial or professional uses that do not expose the general public, and second-hand articles, among other listed exemptions. For most interior wood products sold to the public, however, the restriction is directly relevant.[256]

For biobased wood adhesives, this creates a stronger regulatory stimulus for adhesive systems that reduce or avoid added formaldehyde. Therefore, tannin-, soy-, lignin-, starch-, or other bio-based binder systems may become more attractive if they support panel and furniture producers in meeting the emission test limits. The regulation does not provide an automatic preference to bio-based products, but the advantage is that the adhesive system helps the final wood product stay below the required emission threshold.

Another implication is that testing and proof of compliance become central. The regulation defines that formaldehyde emissions must be assessed under specific reference conditions, namely, EN 717-1, which is a European chamber test method, ensure a harmonized implementation, although in some cases other test conditions may be used if there is a scientifically valid correlation of results. Therefore, biobased adhesive developers will likely need to provide product-level emissions data, not just formulation claims, to support market access in the EU wood products chain.

7.6. Outlook and scenarios of biobased wood adhesives

The wood-based composite panel adhesive market is entering a substitution cycle driven primarily by tightening formaldehyde-emission limits and growing downstream demand for healthier indoor materials. Resin systems, especially UF for interior panels and PF or pMDI for moisture-critical applications, remain hard to displace on cost and performance, however, manufacturers are investing in lower-emission and formaldehyde-free pathways that can scale within existing press and line economics. Near-term growth is likely to concentrate in bridge solutions that preserve current asset bases, such as emission-reducing additives and scavengers and incremental resin optimization, while mid-term opportunity expands for hybrid and bio-based platforms leveraging industrial coproducts and bio-waste (e.g., lignin, tannins, proteins, saccharides, chitosan) to meet circularity and renewable-content targets. Long-term, more disruptive routes, including novel non-formaldehyde crosslinkers and binderless panel technologies, could reshape segments, where energy, press time, and feedstock consistency challenges are overcome. Across all routes, competitive differentiation will increasingly hinge on a three-way trade-off:

- Delivered panel performance
- Manufacturing throughput (press temperature, time, viscosity, and handling)
- Verifiable life-cycle impact.[257]

The current market direction is driving continued expansion of research activity and early commercial development across lignin, tannin, protein, and starch systems, with soy remaining the most commercially mature route. However, there is no broad substitution of conventional wood adhesive systems at present. Soy has established commercial use, while the other major biobased families remain at a more limited industrial scale.[268,270]

The downstream European wood panel market improved slightly by 1.9% in 2024 after a weaker 2023. This provides a more favorable short-term demand context for wood adhesives generally, including biobased options, although it does not by itself demonstrate accelerated substitution toward biobased systems.[273]

Scenarios for the transformation of the biobased wood adhesives market

In a conservative scenario, adoption is continued first through hybrid systems and interior-grade applications rather than rapid full substitution across all panel types. This scenario is supported by the evidence that soy-based formulations are already commercial, but other bio-based adhesives like tannin, starch, and lignin still have limited industrial use, and that some advanced fully biobased systems are presently recommended for interior products.[272,273]

A more positive scenario would require a broader and more reliable feedstock supply from biorefineries or other renewable streams, combined with great evidence that (at least some) modified biobased systems can meet industrial requirements for bond strength, water resistance, curing behavior, and processing. This is supported by an increasing lignin availability from biorefineries and reports of lignin-tannin-pMDI and lignin-glyoxal systems that meet interior-grade requirements.[268,272]

This report does not include market size forecasts, CAGR estimates, or long-range revenue projections because no robust forecast dataset or clearly attributable market model was identified. Overall, the data is stronger on technology development, standards, and downstream panel production than on forecast market size for biobased wood adhesives.

Key uncertainties

One primary uncertainty is the technical performance. Reviews consistently state that poor water resistance, weak adhesion, limited shelf life, high viscosity, and lower strength still constrain many biobased systems. Evidence of a shift would include repeated published results or commercial announcements showing that these systems meet standard panel requirements without substantial reliance on fossil-derived cross-linkers.[257,269,270]

A second uncertainty is feedstock availability. Reviews specifically identify tannin availability as a constraint, while lignin's outlook is linked to new biorefinery streams. Evidence of a shift would include wider commercial supply of adhesive-grade lignin or tannin streams and more industrial use beyond limited-capacity applications.[257,269,270]

The third uncertainty is regulation and specification. If public procurement continues to reward verified biobased content and if low-emission requirements remain important in wood panel markets, these factors would support the adoption of biobased solutions.

A fourth uncertainty is the condition of the underlying wood panel market, as changes are relevant because the wood panel industry is a principal end-use market for these adhesive systems, including biobased ones.

Overall, the outlook for biobased wood-adhesive systems is evaluated moderately positive. Biobased adhesives for wood represent an expanding field, with soy applications already being commercial, while lignin, tannin, and starch progressing through active development. The strongest near-term opportunities appear to be in low-emission panel applications, hybrid formulations, and interior uses where current performance is closer to market requirements. Broader substitution will depend on whether scale, water resistance, bond strength, and processing economics improve sufficiently to compete more directly with established synthetic resin systems.[257,270,272,284]

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