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Wolfgang Falter, Kai Pflug

Value Levers in the Chemicals Industry:

Capital-market-driven unbundling in Germany/Europe versus state-supported scaling and integrated value-chain control in China

Moritz Gutsch, Kai-Uwe Lubisch Roelfs, Simon Albers, Jannis Broeker, Giorgia Carratta, Nils Flothkötter, Marilia Horn, Lisa Wrobel, Karsten Mause

Assessing the Potential of Bio-Based Battery Material Innovations:
Evidence from an Expert Survey

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Robustness Maps: A Scenario-Based Framework for Strategic Feedstock Sourcing under Uncertainty



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Letter from the Editors

Balancing Competitiveness, Innovation and Resilience in the Chemical Industry

The October 2026 issue of the Journal of Business Chemistry brings together three contributions that approach some of the most pressing strategic questions facing the chemical industry today: how industrial structures can combine scale with capital discipline, how emerging technologies can reconcile environmental benefits with technical performance, and how companies can make robust sourcing decisions under growing uncertainty. Although the three papers address very different areas, they share a common concern with the choices that will shape the competitiveness and resilience of chemical businesses in the years ahead. From the structure of global chemical industries to the development of bio-based technologies and the management of critical feedstocks, this issue highlights the need to balance efficiency and performance with flexibility and long-term strategic robustness.

Our first contribution by Wolfgang Falter and Kai Pflug, featured in the Practitioner's Section, takes a comparative look at the very different paths followed by the European and Chinese chemical industries over the past three decades. It explores the contrasting roles of integration, specialization, scale and capital discipline, and asks what the future of industrial integration could look like in a changing competitive landscape.

The second contribution from Moritz Gutsch, Karsten Mause and colleagues turns to bio-based materials for batteries and examines their potential to reduce environmental and supply chain burdens. Based on assessments from 35 experts, the study explores the opportunities and trade-offs associated with different bio-based battery innovations and highlights areas where further technological development and validation will be particularly important.

Our third contribution by Maria Nero and Sandra Gröne addresses the growing uncertainty surrounding industrial feedstock strategies. It introduces a scenario-based framework for assessing the robustness of bio-based, synthetic and mineral feedstocks and demonstrates how companies can use future performance indicators to better understand vulnerabilities and support more resilient sourcing decisions.

Taken together, the three contributions offer different perspectives on a common question: how can chemical companies and the wider industry make strategic choices when the conditions for doing so are becoming increasingly complex? Whether the challenge concerns industrial structures, emerging technologies or raw material supply, the papers in this issue highlight the importance of looking beyond short-term optimization and considering how today's decisions shape long-term strategic flexibility.

We hope that this issue offers valuable perspectives for researchers, industry practitioners and decision-makers, and contributes to the ongoing discussion about the future direction of the chemical industry. Should you have any comments or suggestions, please feel free to contact us at contact@businesschemistry.org. We sincerely thank all authors, reviewers and readers for their continued support and engagement.

Warm regards,

Friederike Fontes
(Executive Editor)

Sabrina Duswald
(Executive Editor)

Practitioners Section

Wolfgang Falter^a, Kai Pflug^b

Value Levers in the Chemicals Industry

Capital-market-driven unbundling in Germany/Europe versus state-supported scaling and integrated value-chain control in China

Since around 1990, the chemicals industries of Germany/Europe and China have diverged. In Europe, integrated groups were broken up to remove conglomerate discounts and maximise enterprise value. This created shareholder value but sacrificed scale, integration and strategic control. In China, the state built large integrated platforms to control value chains, secure supply and gain market power. This won scale and share, but often at the cost of overcapacity and weak returns on capital. Neither model is sustainable in its pure form. Europe needs capital-market-compatible Verbund economics, and China needs greater capital discipline. The causal links are the authors' interpretation, not proven single causes.

Keywords: Conglomerate discount, Corporate unbundling, Verbund integration, State industrial policy, Capital discipline, Value-chain control.

1. Origins of the Industrial Chemicals Industry up to 1990

The industrial chemicals industry developed particularly dynamically during the nineteenth century in Germany and several other European countries, as well as in the United States. Among the formative companies founded during this period were Bayer (1863), BASF (1865), Hoechst (1863), Solvay (1863), Brunner Mond (1873; later ICI), Dow Chemical (1897), Ciba (1884) and Sandoz (1886). These first industrial, integrated chemicals groups combined a very broad range of activities under one corporate roof. These activities included both different types of chemical products (e.g., basic chemicals and intermediates, plastics and fibers, specialty chemicals, crop protection, pharmaceuticals, consumer products) and support functions such as energy supply, research, logistics and site infrastructure. (BASF, 2026; Bayer, 2026; Novartis, 2026)

The companies were not conceived as collections of homogeneous businesses, but as industrial systems. Raw materials (coal/syngas and, later crude oil/naphtha or natural or shale gas/ethane), energy (particularly steam generated in power plants), intermediates, by-products, logistics, infrastructure and research were physically and organisationally interconnected. The economic rationale was therefore not simply portfolio breadth, but the integrated optimisation of material, energy, supply chain and knowledge flows. This Verbund logic was particularly pronounced in Germany, especially by BASF, and became one of the defining competitive advantages of the German chemicals industry. This Verbund principle was successful for around 130 years. Shareholders were mostly national and not worried about the lack of business transparency.

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2. Vertical, Horizontal and Risk-Based Separations to Maximise Enterprise Value

From around 1990 onwards, however, the integrated business model in the Western world came under growing pressure from increasingly international capital markets. Investors began to value individual businesses according to their specific growth, margin, capital-intensity, cyclicality and risk profiles rather than accepting a single valuation for the conglomerate as a whole. The central capital-market question increasingly became: why should a high-growth, IP-protected pharmaceutical or specialty-chemicals business be valued at the same multiple as a cyclical and capital-intensive commodity-chemicals operation?

The capital market recognised, for example, that plastics – used here as an illustration of basic and petrochemicals – are exposed to high capital intensity, cyclical margins, limited differentiation, high energy dependence, environmental and liability risks. Accordingly, such businesses cannot reasonably be valued at the same enterprise-value multiple (EV/EBITDA = Enterprise Value / Earnings before interest, taxes, depreciation and amortisation) as pharmaceuticals, which typically benefit from patent protection, strong

pricing power, high gross margins, comparatively low production intensity and significant barriers to entry.

Pharmaceutical businesses are therefore commonly valued at two to three times the multiples of plastics businesses. Figure 1 illustrates how the valuation gap widened over time. In 1990, pharmaceuticals commanded an enterprise-value multiple that was double that of basic chemicals. By 2025 the valuation gap has increased to more than three. Capital markets increasingly monetised differences in business quality through differentiated valuation multiples.

These pronounced valuation differences triggered one of the largest structural transformations in the history of Western industry. The era of the integrated chemicals conglomerate came to an end. Businesses were separated vertically into chemicals and life sciences, followed by basic chemicals, specialty chemicals, pharmaceuticals, agrochemicals and other segments; and subsequently into increasingly focused customer, technology and application portfolios. The financial logic was straightforward: if a conglomerate contained businesses with fundamentally different valuation profiles, separation could release the conglomerate discount and allow each business to be valued against its own peer group.

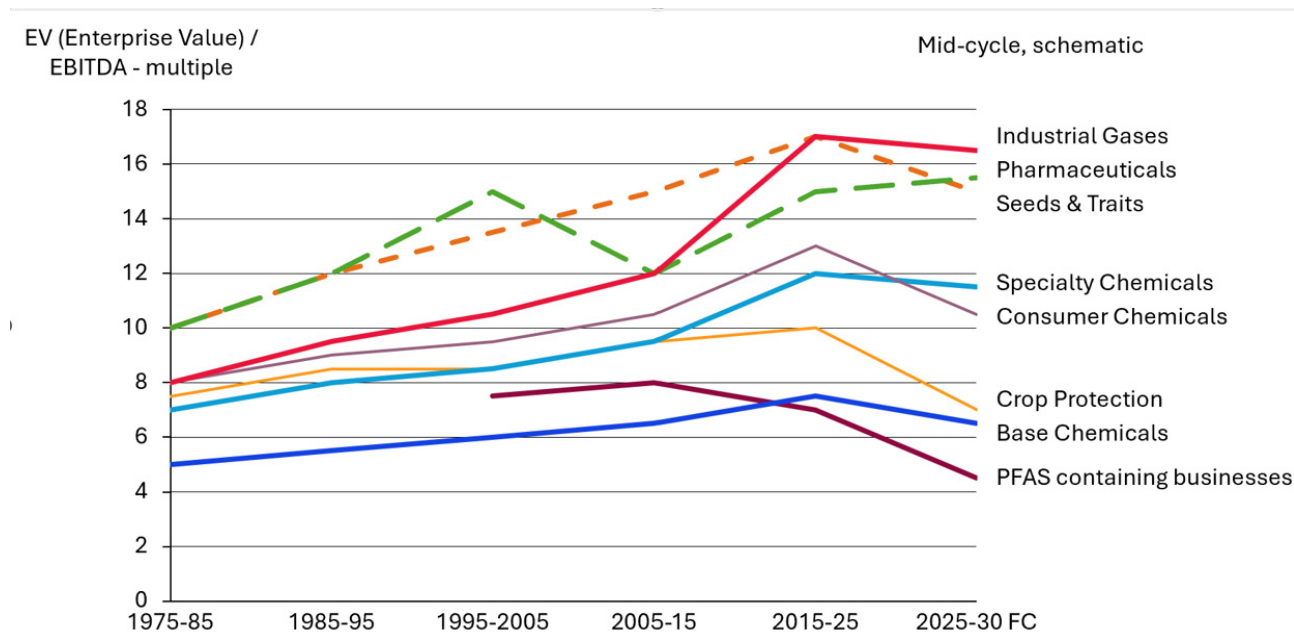


Figure 1. Enterprise values (EV/EBITDA multiples) across chemicals and life sciences, 1975–2025. (source: ELCH 2026); average mid-cycle EV/EBITDA multiples for typical Western transactions.

The spun-off pharmaceutical, agricultural and specialty-chemicals businesses receive their own peer sets and can therefore realise business-specific, generally higher EV/EBITDA valuation multiples. The lower-valued commodity businesses no longer dilute their valuation. In many cases, the sum of the separately valued parts is therefore higher than the market value of the former integrated group (Table 1).

Hoechst between 1994 and 1999 represents the most radical German example. Under CEO Jürgen Dormann, the group began disposing of large parts of its chemical activities. Specialty chemicals operations were transferred to Clariant, industrial chemicals were sold or separated, and the pharmaceutical and agricultural activities were increasingly placed at the centre of the portfolio. In 1999, Hoechst merged with Rhône-Poulenc to form Aventis; Aventis was subsequently acquired by Sanofi. One of Germany's largest integrated chemicals groups had effectively disappeared within only a few years. Its constituent businesses continued to exist, but under numerous different owners and corporate structures. (Clariant, 2026; Infraserv, 2013; Sanofi, 2014)

Bayer proceeded more gradually. In 2005, major chemicals and rubber activities were spun off into LANXESS. In 2015, Bayer MaterialScience was separated as Covestro. Bayer increasingly concentrated on life sciences – pharmaceuticals, consumer health and

crop science. The subsequent acquisition of Monsanto was intended to create a global leader in agriculture, although it also introduced substantial litigation and liability exposure into the group. (Bayer, 2026; Covestro, 2015)

BASF sold its Knoll pharmaceuticals business to Abbott in 2000 and concentrated on chemicals. Its core operations continue to be organised around an integrated network of material, energy and logistics flows. BASF therefore represents an important counterexample to the more radical break-up strategies pursued by Hoechst and others: the group has repeatedly adjusted its portfolio but has retained the Verbund as the organising principle for much of its production system. Businesses outside the Verbund, e.g. coatings, agro solutions, catalysts, batteries were allowed more degrees of freedom outside the Verbund-structures. (BASF, 2000; BASF, 2026)

A similar development occurred elsewhere in Europe. In Switzerland, the chemicals activities of Ciba-Geigy and Sandoz – both with historical roots in textile chemicals and dyes – were combined. Immediately before the creation of Novartis in 1996, their specialty-chemicals operations were separated as Ciba Specialty Chemicals and Clariant. The higher-valued pharmaceutical activities were combined in Novartis, while the chemicals businesses continued independently. This was another example of the capital market separating

Table 1. Illustration of a conglomerate discount using a fictitious integrated chemicals company. (source: ELCH 2026); average mid-cycle EV/EBITDA multiples for typical Western transactions. Fictitious example for illustration only.

Business	Revenues [Mio. €]	EBITDA [Mio. €]	Multiple [EV/EBITDA]	Enterprise Value [Mio. €]
Integrated Chemicals	100	16	6-8x	110
Base Chemicals	35	4	4-5x	18
Specialty Chemicals	25	4	8-11x	38
Agro	15	2,5	10-13x	29
Pharmaceuticals	25	5,5	12-18x	83
Sum of Businesses	100	16	10x	160
Released and monetised conglomerate discount			3x	50

businesses with very different valuation profiles. (Novartis, 2026; Novartis Deutschland, 2021; Clariant, 2026)

ICI spun off Zeneca in 1993. Zeneca subsequently merged with Sweden's Astra to form AstraZeneca, which in 2026 became the subject of reported merger speculation involving US competitor Bristol-Myers Squibb. The remaining 'old' ICI chemicals business lost the pharmaceutical jewel that had supported the group's valuation and was progressively reshaped and sold; AkzoNobel ultimately acquired ICI in 2008. Again, the higher-multiple life-sciences business survived as a major global company, while the traditional chemicals conglomerate disappeared. (AstraZeneca, 2026; AkzoNobel, 2008)

The most radical European example of this transformation in specialty chemicals is the Dutch company DSM (formerly Dutch State Mines). DSM began as a coal-mining company in 1902, transformed itself into a petrochemicals and materials group, then progressively exited commodity chemicals and moved into specialty materials, nutrition and health. The subsequent combination with Firmenich further shifted the portfolio towards nutrition, fragrances and consumer-oriented life-science businesses. The transformation illustrates how far a former heavy-industry group can migrate towards higher-multiple, less capital-intensive activities. (dsm-firmenich, 2025)

In the United States, the same development took place in parallel, but in many cases even more radically. Wall Street has historically been particularly intolerant of uneven business profiles and conglomerate structures. Activist investors, pension funds, mutual funds and private-equity investors repeatedly pressed management teams to divest lower-return businesses, spin off divisions or break up diversified groups where the market value of the parts appeared to exceed the value of the whole.

Monsanto is perhaps the most extreme example. Until the 1980s it was a classic diversified chemicals group, active in acids, plastics, nylon, industrial chemicals and other basic-chemicals businesses. From the 1990s onwards, the company radically repositioned

itself towards life sciences, seed and agricultural biotechnology. Traditional chemicals activities were separated into Solutia in 1997, while Monsanto increasingly concentrated on agricultural technologies and pharmaceuticals. (SEC, 2004)

Act 1: Severe Crisis and the Pharmacia Deal (1997–2000)

Immediately after the Solutia spin-off, the 'new' life-sciences Monsanto came under severe pressure. The group had spent around US\$8 billion acquiring seed companies and building its biotechnology platform. Its agricultural strategy required substantial investment before the expected returns materialised, while the pharmaceuticals business alone was not sufficient to stabilise the group. In 2000, Monsanto therefore merged with Pharmacia & Upjohn to form Pharmacia Corporation. (SEC, 2002)

Act 2: Breaking Up the 'Marriage of Convenience' (2000–2002)

In the merger, Pharmacia was primarily interested in one particularly attractive Monsanto asset: the pharmaceutical business G.D. Searle. Searle had recently launched the highly successful anti-inflammatory drug Celebrex. The agricultural business, by contrast, had a very different risk, growth and valuation profile. Monsanto's agricultural activities were therefore floated separately again, and by 2002 Monsanto had once more become an independent, pure agricultural biotechnology company. Pfizer subsequently acquired Pharmacia, including Searle.

Act 3: Rise to Global Agricultural Leadership (2002–2018)

Over the following fifteen years, the new pure-play agricultural biotechnology company grew rapidly. It became a dominant global supplier of genetically modified seed in crops such as maize, soybeans and cotton and built a powerful portfolio of seed genetics, traits and crop-protection products, including the herbicide glyphosate (Roundup). Monsanto doubled the global seed market value. At the same time, the company became highly controversial because of patent litigation against farmers, intensive lobbying and the broader public debate surrounding genetically modified crops and glyphosate. In 2016, Monsanto unsuccessfully attempted to acquire Syngenta and subsequently approached Bayer CropScience, both without success.

Act 4: The Bayer–Monsanto Transaction (2018 to the Present)

The final act followed in 2018, when Bayer reversed the roles and acquired Monsanto for US\$63 billion. At US\$128 per share, Monsanto's shareholders and management could hardly refuse Bayer's offer. Bayer CEO Werner Baumann intended the transaction to create the ultimate global market leader in agricultural chemicals and seeds. In an effort to eliminate Monsanto's negative public image, Bayer discontinued the Monsanto corporate name immediately after completion; the underlying businesses continued under the Bayer CropScience umbrella. The acquisition is now regarded as one of the most financially consequential transactions in recent German corporate history because Bayer inherited extensive US litigation relating to alleged cancer risks associated with glyphosate. Bayer's market capitalisation subsequently fell sharply. On 19 December 2024, Bayer shares closed at €18.976, and Bayer reported a year-end 2024 market capitalisation of €19 billion. This was roughly one-third of the approximately €56 billion equivalent that Bayer had spent on the Monsanto acquisition. (Bayer, 2018; Bayer, 2026; Bayer, 2025; Wiener Börse, 2024)

Monsanto was not the only US example of decisive corporate break-up. DuPont, arguably the most tradition-rich chemicals group in the United States, attempted for decades to preserve an integrated model but ultimately succumbed to relentless pressure from Wall Street. Its reverse integration through the acquisition of the oil company Conoco was rejected by the stock market as an unwieldy 'mega-conglomerate' and was

subsequently reversed. Conoco was spun off again. DuPont then disposed of its pharmaceuticals business, DuPont Pharmaceuticals, through a sale to Bristol-Myers Squibb. As specialty chemicals, agricultural chemicals and basic chemicals continued to command very different valuations, DuPont spectacularly merged with its long-standing rival Dow Chemical to create the temporary DowDuPont. The sole objective was then to separate the mega-group into three tailored pure-play companies: Dow for basic chemicals/plastics, DuPont for specialty chemicals and Corteva for agriculture. Agro initially remained an integrated Life Sciences business within Corteva. However, significant differences have since emerged between seeds, genetics, chemical crop protection, biologicals and digital agriculture. The separation of the agro pure-play Corteva into the new Corteva (chemical and biological crop protection) and Vylor (seeds, genetics and traits) marks the latest stage of this unbundling process in 2026. (Corteva, 2026a, 2026b) (DuPont, 2019a, 2019b)

Seeds and traits exhibit many characteristics of an IP- and licensing-based business model while chemical and, to some extent, biological crop protection is more similar to traditional chemical business models, as table 2 demonstrates.

Once again, the same principle applies separation promises to free the more highly valued seeds and traits business from the lower valuation multiple attached to crop protection. The separated businesses become smaller, but the expected combined valuation multiple of Vylor and the new Corteva is, driven by

Table 2. Comparison of Agrochemicals Business Models. (source: ELCH 2026/MCC)

Dimension	Seeds Business	Chemical Crop Protection
Customer Retention	High	Lower (pricing pressure, generics)
Key Assets	Patented genetic traits	Manufacturing assets
Key Cost Driver	Development costs	Raw materials costs
Manufacturing Intensity	Low	Higher
Revenues	Recurring	More volatile (competition)
Entry Barriers	Patents, proprietary germplasms	Regulatory approval, testing

Vylor, higher than the valuation multiple of the original integrated Corteva. Here too, the underlying assumption is that the conglomerate discount exceeds the value of the synergies arising from seed treatment, digital applications and integrated offerings.

Another prominent US example is American Cyanamid. Originally founded in 1907 as a traditional chemicals and fertilisers producer, the company built a highly profitable pharmaceuticals division, Lederle Laboratories, during the twentieth century. In the early 1990s, when pure pharmaceutical companies traded at exceptionally high earnings multiples, American Home Products (later Wyeth and now part of Pfizer) acquired American Cyanamid in a hostile US\$9.7 billion transaction. The buyer was principally interested in the pharmaceuticals business; the long-established chemicals operations were rapidly spun off as Cytec Industries and left to operate independently. (C&EN, 1994; FTC, 1995)

While banks and founding families in Europe often continued to shield the old chemical conglomerates, institutional investors – pension funds and Wall Street analysts – increasingly prevailed in the United States. They established the doctrine of the “pure play”: an investor seeking high risk and high returns in pharmaceuticals or biotechnology did not want, within the same equity investment, to finance cyclical polyethylene plants. Investors buying chemical stocks expected to acquire them cheaply (P/E multiples of 8–12x) and to receive a high dividend yield. This uncompromising logic meant that, by the turn of the millennium, the historically evolved integration of pharmaceuticals and basic chemicals had been dismantled even more thoroughly in the United States than in continental Europe.

3. Impact of the Break-up on Market and Competitive Dynamics

According to the authors' estimates, the major integrated Western chemical groups accounted for approximately 25% of global chemical sales in 1990; by 2025, their corresponding share had fallen to only around 12%. BASF illustrates this relative shift particularly well: Group sales amounted to approximately EUR 24 billion in 1990 and just under EUR 60 billion in 2025. Although BASF's sales increased approximately 2.5-fold over

these 35 years (CAGR: 2.7%), the global chemical market expanded sixfold (CAGR: 5.3%). In the 2025 ICIS ranking, Sinopec took first place for the first time, ahead of BASF. (authors' estimate; CEFIC, 2025; BASF, 1994, 2026; ICIS, 2025)

The decline in the global market share of the major Western integrated groups coincided with their capital-market-driven break-up, but cannot be attributed to it alone. Slower demand growth in a maturing European market, comparatively high European energy and feedstock costs, currency effects, and above all the scale of Chinese capacity build-out under state industrial policy have all contributed materially to this shift. The remainder of this article discusses these factors – in particular corporate focus/diversification and vertical (dis-)integration on the Western side, and state industrial policy and industrial resilience on the Chinese and European sides – in more detail.

The deconsolidation of the Western chemicals industry was already being described in the German trade press more than a decade before this article; Haug (2013) provided a comparable overview of market and industry perspectives for the German chemicals sector through 2030. The present article extends that earlier account by tracing how Western deconsolidation and Chinese consolidation diverged further over the subsequent decade, and by drawing out the resulting implications for a capital-market-compatible Verbund model.

4. Separation to Reduce Business and Liability Risks

A relatively recent development, but one that is becoming increasingly visible, particularly in Europe, is the separation of businesses according to their business and sustainability risk profiles – including natural capital consumption, environmental and societal costs, litigation risk, product liability and reputational risk.

This changes the rationale for business separation from the offensive pursuit of a higher corporate valuation towards the defensive mitigation of business and liability risks. Businesses associated with high natural capital consumption, environmental and societal risks, insolvency risk and broader business risks are separated at lower valuations in order to protect the core business. While the principal concerns in chemicals are often

natural capital, environmental and regulatory risks, in pharmaceuticals they are more frequently affordability, product liability, reputation and other societal issues.

Although enthusiasm for sustainability has declined significantly in Europe following the bureaucratic and restrictive requirements of the European Union's Green Deal, these considerations have not disappeared. The relief provided by the Omnibus package, the later introduction of reporting obligations for larger companies and the shortening of the supply chain subject to due-diligence requirements should not obscure the fact that financial and capital markets continue to regard sustainability as a high-priority issue and incorporate it into corporate and business valuations.

A useful practical indicator is the increasing difficulty – or, at the very least, sharply rising cost – of obtaining insurance for manufacturing sites. Insurers, and particularly reinsurers, scrutinise very carefully what is manufactured, where and how it is produced, and where the relevant raw materials and feedstocks originate. Obvious factors lowering valuations have an impact not only on operating costs but also on a number of other aspects, as shown below.

This creates a new valuation discount that cannot be eliminated simply through further corporate separation. It is also becoming increasingly apparent that

sustainability risks do not stop at the legal boundaries of a corporate entity – nor can they be resolved through greenwashing.

5. PFAS as a Typical Example of Sustainability-Related Liability Risk

PFAS (per- and polyfluoroalkyl substances, sometimes referred to as 'forever chemicals') are an example of sustainability-related liability risk. The substance group comprises a wide range of fluorinated substances which, because of their high persistence, are often described as forever chemicals. Some PFAS present significant toxicological or ecological risks. Others perform important technical functions in semiconductors, medical devices, batteries, seals, coatings and high-performance materials. (ECHA, 2025a, 2026a, 2026b)

There is currently no general labelling obligation for PFAS-containing products. Restrictions on PFHxA, its salts and related substances start in the EU/EEA in April 2026. Separately, the EU restriction on PFAS in firefighting foams starts to apply in October 2026, beginning with a ban on PFAS in portable fire extinguishers and additional requirements for continued use of PFAS-containing foams. The broader EU-wide PFAS restriction proposed by five European countries remains under evaluation, with ECHA's scientific committees having issued their 2026 scientific and socio-economic opinions. Given the

examples, schematic

Value Lever	Time	Chemistry	Life Sciences
Starting point: Integration	Before 1990	Integrated Chemicals	
1. Vertical Separation - Sector separation - Value chain separation	1990 – 2015	Chemistry Base & Specialty Chemicals, Fertilisers, Industrial Gases, Fine & Petrochemicals, Polymers, Industrial Chemicals	Life Sciences Pharma & Agro, Food & Feed, Crop Protection, Pharmaceuticals & Generics
2. Horizontal Separation - Market- & Customer- segmentation - Technology- & Pro- ductsegmentation	2010 – 2030	Construction, Transport, Elektro & Elektronics, Mining, Process Industries, Substrates & Applications, Ingredients & Process Chemicals	Human & Animal Health, Care & Cosmetics, Food & Feed, Crop Protection & Seed/Traits, Natural vs. Synthetic
3. Future: Business & Liability Risk Separation	After 2020	Insolvency, Use of Nature Capital, Environmental & Societal Risks	Human- & Eco-toxicity, Biodi- versity, Land-use, Water

Figure 2. Value Drivers in Chemicals and Life Sciences, examples, schematics. (source: ELCH 2026)

essential importance of these substances to industry and medicine, numerous exemptions and transition periods are expected. For investors, the decisive issue is not merely whether a particular substance is prohibited today. (ECHA, 2026a, 2026b)

Value-relevant considerations include those related to legal aspects (possible future regulation, product liability), costs related to customers (e.g., reputational risk, changing customer requirements) as well as costs related to increased insurance premiums and the cost of exploring substitutes.

The discount may therefore also affect businesses that are not formally subject to a general or imminent PFAS ban. This applies, for example, to agrochemical or pharmaceutical active ingredients, which very often contain fluorinated molecular structures or whose manufacturing processes use fluorinated auxiliaries and intermediates. Many of these applications may

be exempted from regulation or treated differently. This does however not change the fact that agro and pharmaceutical ingredients often contain PFAS and that small, water soluble PFAS, like TFA (trifluoroacetic acid) are released into ground waters. Nevertheless, mere proximity to the PFAS issue can already result in higher due-diligence costs, longer approval processes, lower investor demand and lower valuation multiples. (ECHA, 2025a, 2026a, 2026b) This demonstrates that even a highly focused pharmaceutical, agrochemical or specialty-chemicals pure-play is not automatically protected from business risks and sustainability discounts.

What does this PFAS discussion has to do with valuation? The previous unbundling process between highly valued, IP-driven and lower valued, asset-driven businesses was primarily based on the respective business model, as shown in figure 3.

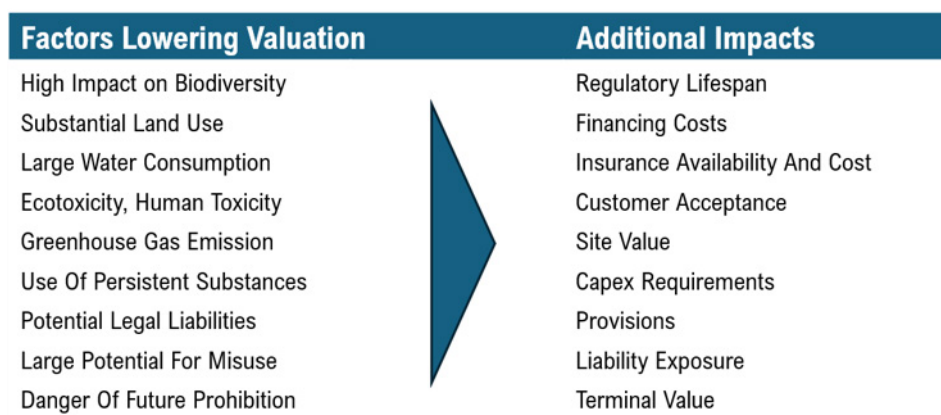


Figure 3. Factors Lowering Business Valuations. (source: ELCH 2026/MCC)

Table 3. Comparison of Chemical Models (Asset-driven versus IP-driven). (source: ELCH 2026/MCC)

Dimension	Asset-driven	IP-driven
Capital Intensity	High	Low
Cyclicality	High	Low
Poduct Type	Commodity	Specialty
Customer Group	Industrial customers	Consumer
Key Value Creation	Via Production	Via Intellectual Property
EV/EBITDA	Lower	Higher

In future, a second valuation dimension will become increasingly important: the physical and societal impact of the business. Two companies may appear economically similar but be valued very differently if one causes critical emissions, produces persistent chemicals, impairs biodiversity or carries substantial remediation risks, while the other does not.

The traditional break-up logic is therefore supplemented by a new question. It is no longer only: How focused is the company? (Pure Play Question). It is also: Which substances, impacts and obligations are embedded in the business? (Sustainability Question)

6. Sustainability Carve-outs Do Not Necessarily Solve the Problem

Separating burdened businesses can improve the parent company's valuation multiple. Examples such as Chemours, Solutia and Tronox show, however, that this does not make the underlying problem disappear.

A company with high debt, limited or no diversification and substantial legacy liabilities may actually be more vulnerable after the spin-off than it was within a larger group. In addition, courts, authorities, lenders and investors increasingly examine whether risks have been allocated in an economically viable and fair manner. Liabilities may subsequently revert to former parent companies or be reallocated among several successor companies. The financial value lever of a separation can therefore quickly be outweighed by environmental and liability risks.

7. Integration Along Value Chains, Technology Platforms and for Import Substitution

China, by contrast, acted strategically and from around 1990 pursued almost the opposite approach. Instead of capital-market-driven break-ups, China focused on consolidation and scale. After the Second World War, China's chemicals industry was only at an early stage of development. Under central direction, production capacities and state-owned structures were gradually combined into larger units. An important milestone was the creation of large state petrochemical platforms,

whose reorganisations gave rise, among others, to today's Sinopec Group. (MIIT et al., 2022; Sinopec, 2025)

While Europe created an increasing number of smaller pure-plays, China built massive new capacity between 2000 and 2010 and systematically integrated companies. In a petrochemicals group such as Sinopec, one important objective is to capture synergies along the physical value chain from fossil feedstock to applied product. But this is only one dimension of integration. Between 2010 and 2020, China embarked on a technological catch-up process, supported by global acquisitions. Wanhua illustrates how a world-leading position was first built around MDI (methylene diphenyl diisocyanate, a key raw material for polyurethane), after which the company expanded backwards, forwards and laterally into adjacent stages of the value chain. At the same time, comparable Verbund structures in Germany were being separated and sold, as illustrated by the sequence Bayer → Covestro → Covestro/Plixxent. (MIIT et al., 2022; Sinopec, 2025; Covestro, 2015)

A third integration route arose from the need to reduce dependence on imported chemicals. Sinochem evolved from a trading company into an increasingly integrated chemicals group and in 2021 was combined with ChemChina to form the state-controlled Sinochem Holdings. (Sinochem Holdings, 2025, 2026)

8. Assessment of the Western Enterprise-Value Model and the Chinese Integration Model

Which model has prevailed? The answer depends on the perspective chosen. From the standpoint of an investor focused on TSR (Total Shareholder Return), ROIC (Return on Invested Capital) and EV/EBITDA (Enterprise Value / Earnings before interest, taxes, depreciation and amortisation), the last 30 years of the EV-maximising model have worked well. Compared with the Chinese model, capital-market pressure tends to reduce empire-building, cross-subsidisation of permanently unattractive businesses, inefficient capital commitment and politically motivated investment. It also forces management to address a highly valuable question: 'Why should this business belong to us in particular?' Integrated groups often lack this discipline.

From the perspective of industrial scale, control of value chains, and industrial and geopolitical power, however, the Chinese model has so far been considerably more successful. The outcome of this industrial policy development is striking. The latest Cefic figures available at the time of revision put China at 48% of global chemical sales and Europe at 12% (Figure 4).

Europe maximised capital productivity and minimised industrial redundancy. From an operational and financial perspective, this was efficient. Particularly during the first 20 years of decoupling, the model delivered strong results. Geopolitically and industrially, however, it was risky, because the question gradually changed from: 'Why should we produce this intermediate ourselves if China offers it at substantially lower cost?' to: 'We can no longer manufacture the final product at all without Chinese intermediates.' As industrial and geopolitical risks have risen globally, the advantages of the Chinese model have become particularly apparent over roughly the last ten years of decoupling. This is precisely the difference between efficiency and resilience. (CEFIC, 2025)

Europe is increasingly recognising this problem. The European Commission launched the Critical Chemicals Alliance (CCA) in 2025; its first General Assembly took place on 13 January 2026 with the objective of making strategically relevant chemicals capacity more resilient and protecting it from closure. This is late, but nevertheless remarkable: Europe is effectively reintroducing a strategic value for chemicals production capacity that goes beyond the individual ROIC of an asset. (CEFIC, 2025; European Commission, 2026a, 2026b)

In summary, the two systems pursue fundamentally different models and objectives: one optimises enterprise and financial value, while the other creates geopolitical dominance and market power.

The Chinese model is not merely an SOE (state-owned enterprise) model. Large private groups such as Hengli, Rongsheng and Shenghong have likewise built highly integrated refining–petrochemicals–polymer/fibre chains. The state, however, provides financing, infrastructure, industrial policy and, in some cases, market protection that enable this strategy. (Sinochem Holdings, 2025, 2026) (MIIT et al., 2022; Sinochem Holdings, 2025, 2026)

A further, increasingly relevant development is the emergence of direct joint ventures between Western and Chinese chemical groups, which combine elements of both models within a single asset. BASF, for example, has operated the integrated BASF-YPC Verbund site in Nanjing together with Sinopec for 25 years (BASF, 2025), while INEOS and Sinopec have more recently agreed a series of joint ventures for a large petrochemicals complex in Tianjin (INEOS, 2025). Such structures allow Western companies to participate in Chinese scale and cost positions and Chinese partners to access Western technology and operating know-how; they may point towards a hybrid organisational form alongside pure Western deconsolidation and pure Chinese state-led integration.

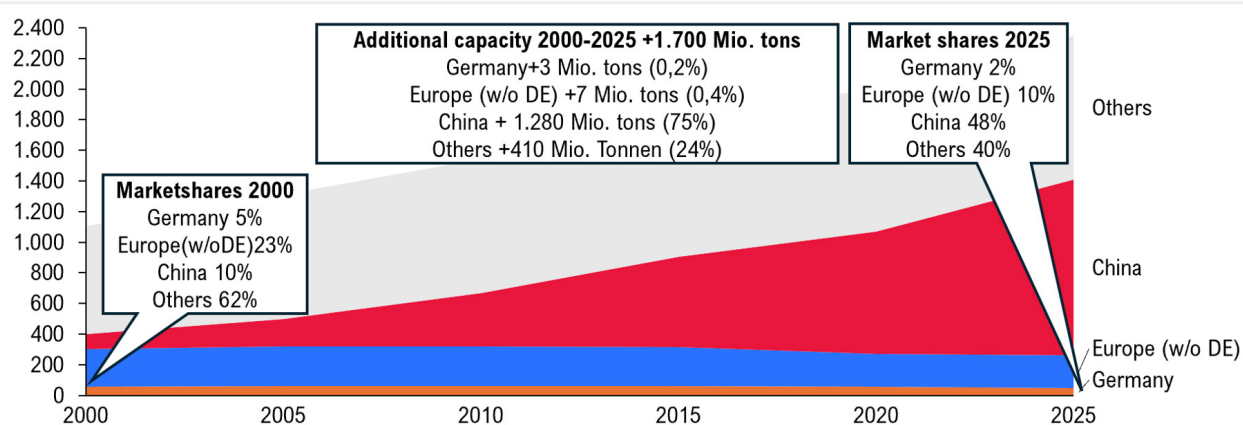


Figure 4. Global chemicals production (excluding pharmaceuticals), million metric tons. (sources: EEA/UNEP; Eurostat; Cefic; VCI; ACC based on ICIS Supply & Demand Database; ELCH 2026)

Table 4. Comparison of Integrated and Enterprise-value Maximizing Business Models in Chemicals. (source: ELCH 2026)

	Enterprise-value maximization	Integrated national chemicals groups
Primary objective	ROIC, multiple, shareholder value	Scale, market share, security of supply, industrial dominance
Organisational principle	Extract homogeneous business models	Control value chains
Capital allocation	Each business must earn its own cost of capital	Capital can be cross-subsidised for strategic purposes
Time horizon	typically 3–7 years	typically 10–20+ years
Commodity business	frequently spun off / sold	strategic component
Specialties / pharmaceuticals	high multiple → valued separately	may remain integrated downstream in the chain
Overcapacity	close / sell	partly accepted deliberately
Pricing power	through differentiation	through cost, volume and market position
Crisis resilience	lower in the event of supply-chain disruption	higher with vertical integration
Capital-market valuation	high priority	secondary
Geopolitical power	rather weak	very strong

9. Neither the Western nor the Chinese Model Is Sustainable in Its Current Form

Both models are increasingly showing cracks and are unlikely to be sustainable in their present form. Germany and Europe have taken the capital-market-oriented model too far: the marginal benefit of further separation is declining and, in some cases, turning negative. Excessive fragmentation creates units that are too small to compete successfully over the long term. China seeks to control entire industrial value chains and has moved too far in the opposite direction.

Under such a logic, individual stages of a value chain may even earn a 0% ROIC if they secure supply, reduce downstream costs, displace competitors, generate economies of scale, reduce import dependence or

support exports at other stages. From a financial and Western portfolio perspective, this represents poor capital allocation. From an industrial and geopolitical perspective, however, it may be entirely rational. Yet China's overinvestment in massive excess capacity and weak capital discipline, combined with slower domestic demand growth, are producing unsustainable business models and an intense struggle for survival. (CEFIC, 2025; Reuters, 2025a, 2025b)

10. A Capital-Market-Compatible Verbund Model

What should be done? Instead of 'continuing to separate different business models', the principle should be that 'the Verbund value of groups of assets must earn its cost of capital'. Reviewing chemical value-chain trees together with utility supply and logistics can help protect integration where it creates value. The economic Verbund

value of material, energy, infrastructure, supply-chain, know-how and resilience synergies should be quantified and considered alongside the stand-alone value of individual assets in investment and portfolio assessments. Germany and Europe should not re-integrate companies. They should integrate production.

Critical chemicals value chains as the ones shown in table 5 should therefore be defined.

The next question should be: which two to four production stages must Europe under no circumstances lose simultaneously? This is fundamentally different from saying, 'this plant has a poor 2027 EBITDA margin, so close it'. Analogous to energy or defence infrastructure, Germany and the EU should maintain a list of perhaps 50–100 key chemicals plants or production capabilities. Not every ammonia, PE or TiO₂ plant is strategic. But if the last European plant producing a critical intermediate disappears, the economic damage is of a fundamentally different order.

Stand-alone ROIC should therefore be supplemented by a 'systemic Verbund ROIC'. A plant earning a 3% ROIC may enable value creation of 10% or more elsewhere in the chain. Companies should not automatically spin off such assets. The consideration should also include aspects such as securing feedstock or utilizing by-products. The question should therefore not be: 'Asset

A does not earn its WACC → sell it.' It should be: 'What happens to the EBITDA, risk profile and strategic value of B–F if A disappears?'

A particularly relevant issue in Germany is the role of independent chemicals parks. Where financial investors own the park infrastructure, interests can diverge quite easily. Chemicals companies require energy, logistics and infrastructure services at the lowest possible competitive cost. Chemicals-park owners, by contrast, seek a stable, competitive return on their investment. This is particularly important for mandatory services that cannot readily be sourced externally. The scope for profit maximisation is naturally constrained by the fact that, under uneconomic conditions, chemicals companies themselves can no longer survive at the site.

Infraserv Höchst, which operates the Höchst Industrial Park in Frankfurt, illustrates one way of managing this tension: rather than being owned by a purely financial investor, it is held jointly by several of the chemicals and pharmaceuticals companies operating on the site (Wikipedia, 2026). Ownership structures of this kind, in which tenant companies hold a stake in the site operator, can help align infrastructure investment with the operating companies' own interests and may preserve some of the economic benefits of Verbund production even where full corporate integration is neither possible nor desirable.

Table 5. Examples of Chemical Value Chains For Which Integration May Be Critical. (source: ELCH 2026)

Chain	What strategically belongs together
Chlor-alkali	Electricity → chlorine/NaOH → PVC, isocyanates, epoxides, pharmaceutical/agrochemical intermediates
C2/C3	Naphtha/LPG → cracker → ethylene/propylene → EO/PO, PE/PP, oxo chemicals, acrylates
Aromatics	Refinery → benzene/toluene/xylenes → PU, PA, PET, coatings, pharmaceuticals
Sulphur	Refineries → sulphur/H ₂ S → H ₂ SO ₄ /sulphides → fertilisers, metals, specialty chemicals
Fluorine / phosphorus	Raw material → basic chemicals → electronics, batteries, pharmaceuticals, crop protection
Pharma / agro	Basic chemicals → key intermediates → active ingredients → formulation

More important, however, is often the failure to make the investments required for a future competitive energy, material and logistics Verbund under such ownership and incentive structures. This can progressively undermine the economics of the companies located at the site. Even today, decentralised steam-generation solutions are often more economical than steam generated centrally in chemicals-park power plants and distributed across the site. Similar considerations apply to other services. Industrial parks therefore need to be closely integrated economically with the chemical companies operating on them, without necessarily merging the companies themselves. This is probably the most important practical point – but also the one that is most difficult to implement.

Even then, energy policy must be treated as chemicals policy. Germany cannot strategically retain energy-intensive basic chemicals while permanently providing electricity and gas at structurally higher costs than in the United States, the Middle East or China. Subsidy programmes alone cannot compensate for this. Strategically necessary basic chemicals production in Europe requires long-term, predictable costs for inputs such as electricity, hydrogen/ gas as well as for infrastructure/ grid costs and emission fees (carbon tax).

The EU action plan for the chemicals industry is already moving more strongly towards protecting critical production capacities and strengthening resilience. This logic, however, needs to be applied more consistently to value chains rather than to individual companies. (European Commission, 2026a, 2026b)

When responding to Chinese dumping, Europe should not react plant by plant. China plays value chains; Europe often plays individual customs tariff numbers (HS codes). If, for example, an integrated Chinese producer accepts upstream losses in order to build global downstream market share, an anti-dumping duty on product X alone may not be sufficient. Europe should examine the economics of the Chinese chain as a whole and, where appropriate, take greater account of value-chain effects, state financing, energy prices, capital costs and cross-subsidization. European competition law has traditionally focused very strongly on competition within Europe. For globally traded chemicals, the question should more often be: 'Is the relevant competition BASF versus

Evonik – or Europe versus Chinese platforms with five to ten times the scale?' In some areas, European champions or shared platforms may make more sense than five companies that are each too small.

11. What Should China Do?

For China, the task is almost the mirror image. China has now taken some of the advantages of integration too far. The central challenge is no longer: 'How do we build complete value chains?' This has largely been achieved. China does not need to disintegrate production, but it does need to reduce overcapacity in basic chemicals, focus more strongly on specialty chemicals, impose greater discipline on capital allocation, support a broader ownership base and permit domestic consolidation. (European Commission, 2026a, 2026b; Reuters, 2025a, 2025b)

Four measures could help China avoid systematically building excess capacity and destroying capital and margins:

1. From 'maximum capacity' to 'maximum ROIC'

Not every province needs a refinery, a cracker, a PTA, polyester, methanol and chlor-alkali plant. China should accelerate the closure of older and less efficient capacity in particular. (Reuters, 2025a, 2025b) The country has already begun to address the overcapacity problem more actively. (Reuters, 2025a, 2025b)

2. Preserve integration – but consolidate commodity capacity

China should not destroy value chains. Instead, it could, for example, replace ten mediocre plants with four very large integrated plants. This would preserve economies of scale, security of supply, infrastructure and market power while improving ROIC.

3. Make state financing more selective

As long as capital is available almost irrespective of returns, overinvestment is inevitable. The decisive reform would therefore be: strategic importance must not mean automatic financing of every project. Strategic industrial policy should secure the value chain, not every individual producer.

4. From cost leadership to value leadership

China has now achieved scale advantages in many areas of chemicals. The next stage of value creation is: Commodity → Specialty → Formulation → Application Know-how → IP – precisely the progression that Europe spent decades perfecting.

12. What Does a 'Capital-Market-Compatible Verbund Model' Mean?

Germany does not need to re-integrate companies. It needs to integrate production. China does not need to disintegrate production. It needs to discipline capital allocation.

Germany: „Integrated value chains without integrated ownership.“

China: „Integrated value chains with disciplined capital allocation.“

This could indeed give rise to a new and potentially superior long-term model for the chemicals industry:

a capital-market-compatible Verbund model. It combines the capital discipline of the Western model with the industrial advantages of integrated value chains – in Germany and Europe with a stronger emphasis on ROIC and resilience, and in China with a stronger emphasis on ROIC and strategic market power.

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Table 6. Key Issues and Solutions for German/European and Chinese Chemical Companies. (source: ELCH 2026)

	Germany / EU	China
Key Issue	Excessive fragmentation	Excessive capacity expansion
Solution by Aspect		
Companies	Fewer further spin-offs	Fewer additional capacities
Integration	Increase physical integration again	Preserve physical integration
Ownership	May remain separate	Consolidate more strongly
Capital discipline	Relax somewhat for strategic assets	Increase significantly
State	Secure value chains	Limit overinvestment
Competition policy	Take global scale into account	Permit domestic consolidation
Commodity	Retain strategic minimum capacity	Reduce overcapacity
Specialty	Continue to focus	Expand substantially
Objective	Resilience + ROIC	ROIC + market power

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Statement of AI Usage

In preparing this revised manuscript, the authors used AI-based writing assistants (Claude, Anthropic and ChatGPT, OpenAI) to support the reformatting of in-text citations and the reference list in line with the Journal's submission guidelines, to help incorporate the reviewers' comments into the text, and for language editing. All analysis, arguments, data interpretation and conclusions are the authors' own; the authors reviewed, edited and take full responsibility for the entire content of the article, including any text drafted with AI assistance.

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Note: In-text citations follow the format (author, year); full references are listed alphabetically below. The authors' own assessments and recommendations, ELCH (2026) figures, and statements explicitly identified as the authors' estimates reflect the authors' professional judgement and are not externally substantiated factual claims; they are distinguished in the text from documented, individually sourced facts.

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Appendix

Table A1. Typical 2025 EV/EBITDA Multiples, Business Models and Sources of Pricing Power. (source: ELCH 2026), proprietary analysis based on company and transaction data; indicative ranges, cross-checked against Damodaran (2026) where comparable sector classifications exist.

Business Segment	Business-model logic	Sources of pricing power	Limits to pricing power	Typical EBITDA margin	Typical EV/ EBITDA
1. Petro-chemicals	Large continuously operated plants converting oil, gas or naphtha into olefins, aromatics, polymers and intermediates. Economics driven by scale, feedstock integration, utilisation and site costs.	Cost leadership, favourable feedstocks, Verbund sites, logistics position, regional supply shortages.	Largely interchangeable products; world-market and import parity; high fixed costs drive aggressive volume competition during overcapacity.	8–18%, highly cyclical	5–8×
2. Fertilisers	Production of ammonia, urea, nitrate, phosphate and potash fertilisers. Value is primarily created through access to gas, phosphate or potash resources.	Resource and gas advantages, trade barriers, regional logistics, temporary supply shortages.	Commodity character; farmers respond to crop prices; supply from China, Russia and the Middle East; high cyclicity.	15–35%, highly cyclical	4–7× mid-cycle
3. Industrial gases	Local supply networks, on-site plants, pipelines and long-term take-or-pay contracts. The gas itself is simple; infrastructure and supply reliability are decisive.	Very high switching costs, customer-specific plants, long-term contracts, local oligopolies, safety-critical supply.	Regulatory control, large customers with bargaining power; electricity costs may only partly be passed through.	25–40%	12–17×
4. Industrial chemicals	Chlor-alkali, acids, alkalis, silicates, technical salts and other industrial basic chemicals. Markets are often regional because of high transport costs.	Local plant position, by-product integration, transport costs, security of supply.	Low product differentiation; energy and raw-material costs; overcapacity; large industrial buyers.	10–20%	6–9×

Business Segment	Business-model logic	Sources of pricing power	Limits to pricing power	Typical EBITDA margin	Typical EV/ EBITDA
5. Fine chemicals / custom manufacturing	Multi-step synthesis of smaller volumes, often customer-specific. Model based on process know-how, quality, plant flexibility and regulatory documentation.	Qualification effort, confidential processes, long customer relationships, low material cost in final product, high cost of failure.	Project concentration, customer insourcing, Asian competition, volatile utilisation.	15–25%	8–12×
6. Renewable feedstock chemicals	Conversion of vegetable oils, sugar, starch, cellulose or fermentation products into oleochemicals, surfactants, polymers and functional ingredients.	Sustainability credentials, certified supply chains, specific functionality, customer CO ₂ targets.	Many products compete directly with petrochemical alternatives; feedstock prices and green premiums are volatile.	10–22%	7–11×
7. Specialty chemicals	Selling a function or performance improvement rather than a molecule: additives, coating raw materials, electronic chemicals, catalysts, water treatment etc.	Small cost item for customer, high impact on product/process, formulation know-how, technical approval, high switching risk.	Pseudo-specialties may commoditise; customer consolidation; Chinese imitators; portfolio heterogeneity.	18–30%	9–14×
8a. Paints and coatings	Formulation and brand model combining raw materials, colour systems, distribution and application technology across OEM, refinish and decorative markets.	Specifications, colour consistency, OEM approvals, workshop/dealer networks, brands, low coating cost relative to coated product.	Raw-material costs, private labels, powerful OEMs and DIY retailers, local competitors.	15–25%	9–13×

Business Segment	Business-model logic	Sources of pricing power	Limits to pricing power	Typical EBITDA margin	Typical EV/ EBITDA
8b. Adhesives and sealants	Highly application-specific formulations that bond components or enable processes. Often low material share but high importance to product quality.	Customer design-in, certifications, automated application processes, high requalification or failure costs.	Standard products and construction adhesives are less differentiated; exposure to automotive, construction and electronics cycles.	18–30%	10–15×
8c. Home care	Formulation, branding, marketing and distribution of laundry, cleaning and household products. Production itself is relatively simple.	Brand, shelf space, consumer habits, product innovation, distribution and advertising budgets.	Private labels, strong grocery-retail bargaining power, low consumer switching barriers.	15–25%	9–14×
9. Cosmetics and personal care	Brand-, innovation- and distribution-led business; product cost is often only a small share of selling price. Premiumisation and high marketing intensity.	Brand, trust, emotional differentiation, influencers and distribution, formulation and claims innovation.	Fashion trends, high customer-acquisition costs, weak loyalty for weaker brands, regulatory claims.	15–30%	11–18×
10. Crop protection	Development, registration, production and marketing of patented active ingredients, formulations and increasingly integrated seed/digital offerings.	Patents, regulatory approvals, field trials, efficacy, distribution channel, development costs, long market-entry times.	Patent expiry, generics, resistance, weather, channel inventories, political bans and liability risks.	18–30%	7–11×
11. Biotechnology	Use of living systems for therapeutics, enzymes, ingredients or industrial processes. Value derives primarily from IP, platforms and clinical/technical probability of success.	Patents, proprietary organisms/ platforms, data, regulatory exclusivity, potentially unique efficacy.	Very high development and scale-up risks; binary trial outcomes; often no positive EBITDA.	Often negative; commercial businesses 20–50%	Profitable platforms c. 12–25×

Business Segment	Business-model logic	Sources of pricing power	Limits to pricing power	Typical EBITDA margin	Typical EV/ EBITDA
12. Generics	Rapid, cost-efficient manufacture and approval of off-patent medicines; scale through global product portfolios and distribution.	Regulatory know-how, security of supply, complex generics, sterile products, biosimilars, vertical API integration.	Tenders, steep post-patent price declines, US pricing pressure, many competitors, quality and FDA risks.	15–25%	6–10×
13. Research-based pharmaceuticals	Investment in research, clinical development and approval; after success, time-limited monopoly rents from patent and regulatory protection.	Patents, clinically superior products, regulatory exclusivity, physician/payer access, high barriers to entry.	Patent cliffs, reimbursement pressure, clinical risk, regulatory intervention, concentration on individual blockbusters.	25–45% for established companies	9–15×
14. Chemical distributors	Purchasing, storage, financing, bundling, technical advice and small-lot delivery of chemicals. Value derives from network and working-capital management.	Exclusive supplier mandates, local warehouses and licences, broad customer base, technical advice, small order sizes.	Suppliers can sell direct; low differentiation in standard chemicals; working-capital and price risk.	7–13%	7–11×

Research Paper

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Assessing the Potential of Bio-Based Battery Material Innovations: Evidence from an Expert Survey

Bio-based materials could reduce the environmental and supply-chain burdens of batteries, but their technical and economic consequences remain uncertain. This paper addresses these uncertainties by eliciting judgments from 35 experts who evaluated six bio-based battery innovations across various dimensions, including specific energy, lifetime, material cost, production cost, carbon-dioxide emissions, and recycling capability. Across 210 innovation ratings, favorable impacts were most frequently expected for carbon-dioxide emissions (81.9%), material cost (70.5%), recycling (61.9%), and production cost (53.8%). By contrast, 55.7% of ratings anticipated negative impacts on specific energy and lifetime. An exploratory ordinal scoring exercise identified bio-based anode binders as having the most favorable overall profile, whereas bio-based cathode active material presented the greatest performance concerns. Most maturity assessments placed the innovations within ten years of practical readiness. These findings reveal a consistent tension between environmental promise and electrochemical performance, identifying priorities for laboratory validation, lifecycle assessment, and targeted research investment.

Keywords: Battery research, Bio-based battery materials, Expert elicitation, Technology assessment, Innovation management.

1. Introduction

Rapid growth in battery deployment is increasing demand for raw materials, energy-intensive manufacturing, and effective end-of-life management (Ihlbrock et al., 2025). Although battery electrification can reduce emissions during vehicle or device operation, these benefits do not eliminate environmental burdens

associated with material extraction, component production and recycling (Gutsch and Leker, 2024). Substituting renewable, biologically derived or bio-processed materials for conventional battery components could reduce lifecycle emissions, facilitate material recovery and diversify supply chains (Liedel,

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2020; Liu et al., 2021). Bio-based materials may be relevant to electrodes, binders, separators, electrolytes and supporting components, but their suitability depends on more than renewable origin. They must also satisfy demanding requirements for energy density, stability, manufacturability, cost, and safety (Dühnen et al., 2020).

Research in this area is therefore confronted by a prioritization problem. Many candidate technologies appear environmentally attractive, yet comparative evidence remains limited and maturity varies substantially among pathways. Decisions about which concepts should proceed to laboratory development, pilot manufacturing, or system-level assessment often must be made before reliable engineering and lifecycle data are available. Expert elicitation cannot replace those data, but it can expose shared expectations, uncertainty, and potential trade-offs at an early stage (for more details on the expert elicitation method, see e.g. Morgan, 2014 and Hanea et al., 2021).

In this study, we elicited expert assessments of six proposed bio-based battery innovations: (I) Bio-based graphite, (II) bio-based cathode active material (CAM), (III) bio-based separators, (IV) bio-based electrolytes, (V) bio-based anode binders, and (VI) bio-based cathode binders. Respondents evaluated the expected direction and magnitude of each innovation's impact across several assessment dimensions: specific energy, battery lifetime or cycling stability, material cost, production cost, carbon-dioxide (CO₂) emissions, and recycling capability. We also asked the experts to estimate the time required for each innovation to reach maturity. More specifically, we posed three questions: First, whether experts anticipated systematic environmental, economic or performance effects. Second, whether any innovation presented a comparatively favorable balance across these dimensions. Third, and finally, whether perceived benefits were aligned with expectations of near-term maturity.

This study was conducted as part of the interdisciplinary research project BIOSTORE ("Biologization of Batteries and Materials: Developing the Battery of the Future"), located at the University of Münster, Germany. The BIOSTORE project addresses the pivotal challenge of sustainability in the battery sector. More specifically, it

investigates the potential of the so-called biologization of batteries – a technique through which some commonly used battery components are replaced by bio-based alternatives. This process potentially enables the development of more sustainable energy storage devices while ensuring comparable performance. The BIOSTORE project comprises experts from a wide range of disciplines, including biology, chemistry, engineering, political science, economics, and law. At the time the expert survey and data analysis were conducted, the authors of this study were postdoctoral researchers within this research project. For more information on this project, see Schmid et al. (2025) and Bröker & Flothkötter (2026).

The paper proceeds as follows. Section 2 outlines the methods, detailing the survey design and the data analysis approach. Section 3 presents the results of the study. Finally, Section 4 offers a discussion of the findings along with an outlook on future research.

2. Methods

To assess how selected bio-based battery innovations could potentially affect performance, costs, and the environmental footprint, we conducted an online expert survey between December 2025 and January 2026. The survey provides the empirical basis for this study. Regarding the survey design, as briefly mentioned in the introduction, the questionnaire described the following six candidate bio-based battery innovations:

(I) Bio-based graphite is an alternative to conventional graphite used in lithium-ion batteries. Unlike traditional graphite sourced from fossil resources, bio-based graphite is derived from renewable biomass, such as vegetable carbon (biochar). This material aims to reduce environmental impact while offering comparable performance.

(II) Bio-based cathode active materials are innovative alternatives to conventional metal-based cathodes in lithium-ion batteries. Instead of relying on mined metals like cobalt or nickel, these materials utilize organic compounds derived from renewable biomass sources. They aim to reduce dependence on critical raw materials while providing stable electrochemical performance and improved environmental sustainability.

(III) Bio-based separators are a novel alternative to conventional battery separators made from fossil-derived polymers such as polyethylene (PE). These innovative materials are produced from renewable sources such as polysaccharides (e.g., cellulose or chitosan). They aim to maintain or improve battery safety and performance while reducing environmental impact and dependence on fossil resources.

(IV) Bio-based electrolytes represent an emerging class of electrolyte solvents designed to replace conventional fossil-derived mixtures such as ethylene carbonate (EC) and ethyl methyl carbonate (EMC) in lithium-ion batteries. These alternatives are derived from renewable feedstocks and aim to match or exceed the electrochemical stability, ionic conductivity, and safety performance of standard solvents. The substitution may influence overall system performance, cost structures, and environmental impact.

(V / VI) Bio-based binders serve as renewable alternatives to traditional polymer binders in lithium-ion batteries. Sourced from natural materials such as polysaccharides (starch, alginate) or lignin, these binders aim for strong adhesion of active materials to current collectors while maintaining flexibility and conductivity. By replacing petroleum-derived binders, they contribute to greener and more sustainable battery manufacturing. The type of binder also affects the processing of electrodes. As this can differ for anodes and cathodes, the experts were questioned separately regarding the anode and cathode side, resulting in a total of six different innovations.

The full descriptions of these battery innovations were provided to the survey participants in the questionnaire, which can be found in the Appendix to this paper. Participants rated each innovation across several criteria: specific energy, lifetime or cycling stability, material cost, production cost, carbon-dioxide emissions, and recycling capability.

For each dimension, responses comprised strong negative impact (>15%), moderate negative impact (5–15%), weak negative impact (<5%), weak positive impact (<5%), moderate positive impact (5–15%), and strong positive impact (>15%). Alternatively, the participants could choose “I don’t know”. Positive responses indicated improvement relative to NMC811-graphite lithium-ion

battery cells which served as a reference point/cell; for cost and emissions, improvement meant a reduction. “I don’t know” represented insufficient knowledge and was not treated as a neutral judgment.

Participants also assessed time to maturity as under five years, five to ten years, more than ten years, never, or “I don’t know”. As mentioned above, the survey was administered online. Participants were recruited through e-mail and were eligible if they self-identified as experts in the battery field. Regarding the data analysis, it should be noted that all data processing and visualizations were conducted using Python. The data analyzed in this study are available from the authors upon request.

3. Results

3.1 Environmental promise accompanied by performance concerns

Thirty-five participants completed the survey, comprising 26 respondents from academia, six from industry, and three reporting other professional roles. Since each participant evaluated all six innovations, the survey yielded 210 innovation-level ratings. To account for this structure, analyses distinguished between the 35 participants as the independent observational units (i.e., 35 participant-level observations) and the individual ratings (i.e., 210 innovation-level ratings). Finally, response distributions were summarized descriptively by impact dimension and innovation.

Across the complete set of ratings, experts expressed the greatest optimism about carbon-dioxide emissions. Of the 210 assessments, 81.9% classified the expected emissions effect as positive, meaning that the innovation was expected to reduce emissions relative to an NMC811-graphite cell. Material cost received favorable assessments in 70.5% of ratings, recycling capability in 61.9%, and production cost in 53.8%. These responses suggest that experts regarded the principal value of bio-based battery materials as being environmental and resource-related rather than serving as an immediate route to improved electrochemical performance.

Performance assessments were substantially less favorable. Negative impacts were reported in 55.7% of ratings for specific energy and in 55.7% for lifetime or

cycling stability. Thus, the same innovation portfolio that was widely expected to improve emissions, costs or end-of-life management was also expected to create performance penalties. This pattern represents the central result of the elicitation: experts did not interpret biological origin as an unqualified sustainability advantage. Rather, they anticipated a trade-off in which upstream and end-of-life benefits might be achieved at the expense of energy storage performance or durability.

3.2 Innovation profiles reveal different research priorities

To compare the six innovation profiles in Figure 1, the ordered response categories were transformed into an exploratory score as follows: strong negative impact (-2), moderate negative (-1), weak negative (-0.5), weak positive (+0.5), moderate positive (+1), and strong positive impact (+2). The response "I don't know" was excluded from the data evaluation, reducing the number of evaluated responses to 24-34 answers per category (indicated by the number (n) in Figure 1).

The heatmap in Figure 1 demonstrates that expected environmental benefits were comparatively consistent across the innovation portfolio, particularly for carbon-dioxide emissions. By contrast, specific energy and lifetime varied more strongly among innovations and generated most of the negative scores. Innovation V, bio-based anode binders, had the most favorable aggregate profile under the exploratory scoring convention. Its relative advantage arose from favorable emissions,

recycling and cost assessments with comparatively limited performance penalties. Innovation II, bio-based cathode active material, received the least favorable assessments for specific energy and lifetime.

These profiles should not be mistaken for a definitive league table. The innovation identifiers are nominal, the assigned scores are not measurements on a continuous scale, and the sample does not support precise population estimates. More usefully, Figure 1 distinguishes three possible development strategies. Innovations with favorable environmental assessments and limited performance penalties are candidates for accelerated validation. Innovations with substantial environmental promise but pronounced energy or lifetime penalties require coupled materials and cell-engineering research. Innovations characterized by uncertainty across several dimensions require better definition and preliminary evidence before comparative prioritization is meaningful.

3.3 Most pathways are expected to mature within a decade

Respondents also estimated the time required for each pathway to reach maturity using the following categories: less than five years, five to ten years, more than ten years, never, and "I don't know". Across all 210 assessments, five to ten years was the most common response, accounting for 38.1% of ratings, while 30.5% anticipated maturity in under five years. Taken together, 68.6% of ratings placed maturity within ten years.

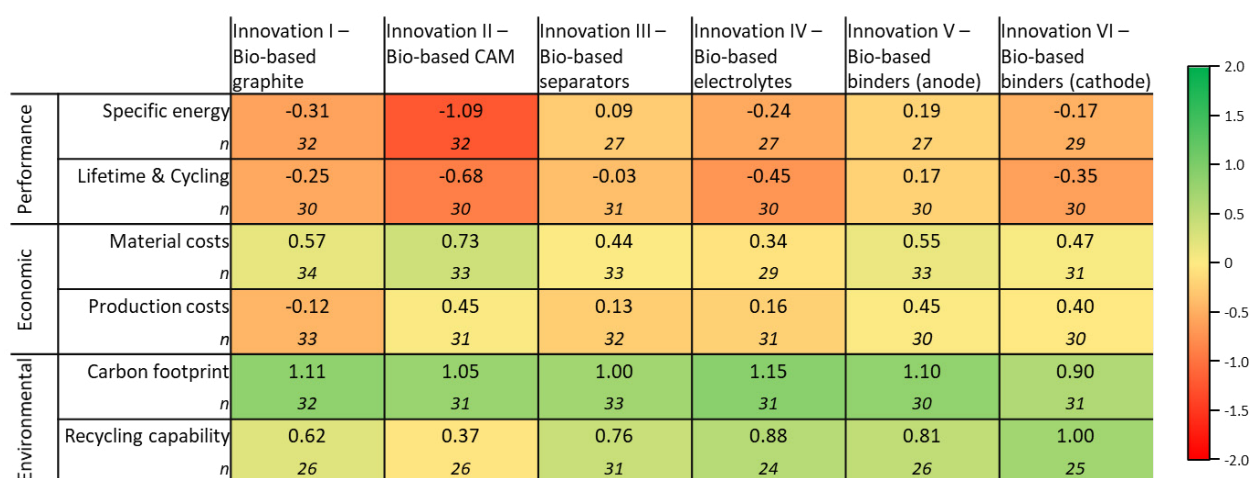


Figure 1. Heatmap of mean ordered scores by innovation and impact field (green = positive, red = negative, n = number of evaluated responses).

As summarized in Figure 2, these maturity distributions nevertheless differed substantially among the innovations. Bio-based graphite, bio-based separators and bio-based anode binders attracted the largest proportions of assessments within the shorter maturity categories, whereas bio-based CAM and bio-based electrolytes received more assessments of over ten years or “I don’t know”. These differences matter because a favorable environmental profile has limited immediate relevance if the underlying technology remains technically immature. Conversely, a moderately beneficial pathway that can be integrated into existing manufacturing processes may deliver earlier cumulative sustainability gains than a more ambitious but distant alternative.

Maturity judgments should not be interpreted as deployment forecasts. Respondents were asked to summarize expectations rather than construct probabilistic forecasts from technical-readiness, manufacturing and market evidence. The distributions are therefore better understood as indicators of perceived development difficulty. They can guide the sequencing of follow-up work but cannot establish commercialization dates.

3.4 Professional groups provide only exploratory contrasts

Figure 3 presents normalized impact-response distributions separately for academic and industry respondents. While both groups showed broadly favorable expectations for environmental dimensions alongside shared concerns about specific energy and lifetime, some apparent descriptive differences are visible across roles. However, because the industry (n=6) and “Other” (n=3) subsamples were too small compared to academia (n=26), these role comparisons were not tested inferentially.

The role comparison is consequently descriptive. Normalization prevents the larger academic group from dominating the visual display, but it does not overcome the uncertainty associated with small group sizes. No claim of systematic academic–industry disagreement is warranted from these data. A larger, deliberately stratified elicitation would be needed to determine whether views differ by sector, disciplinary background, battery expertise or position within the innovation chain.

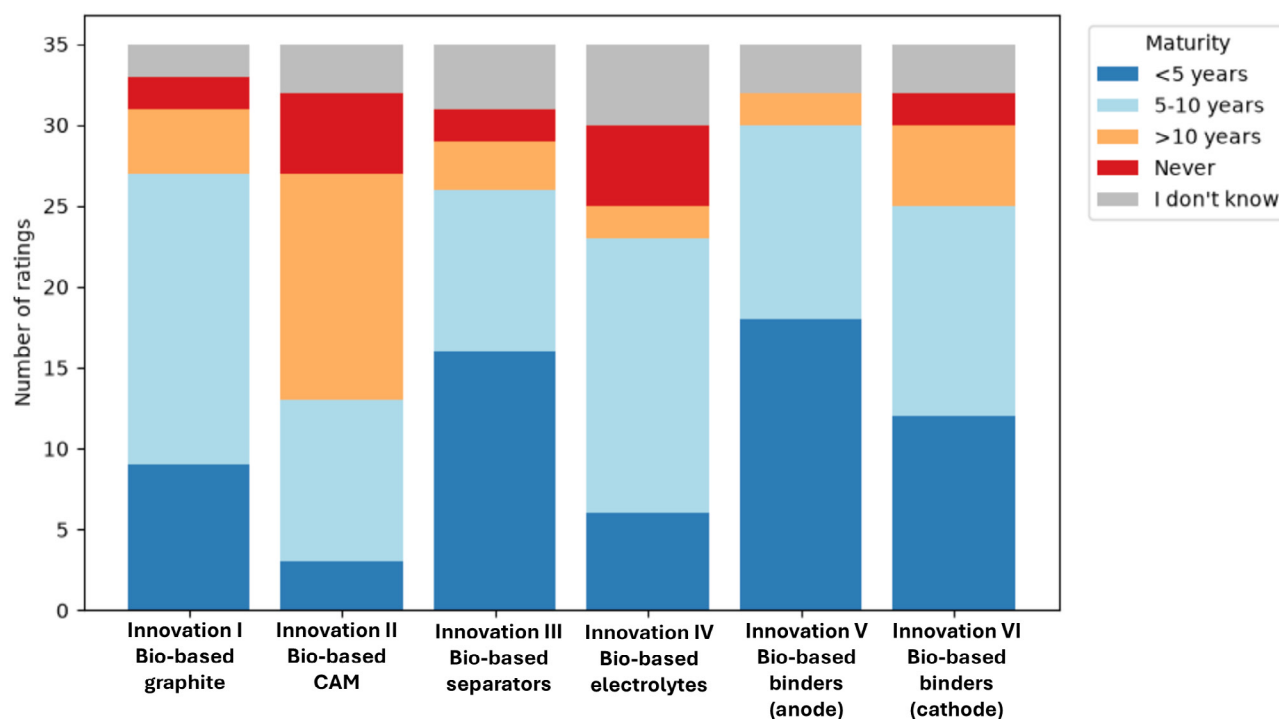


Figure 2. Maturity expectation distributions by innovation.

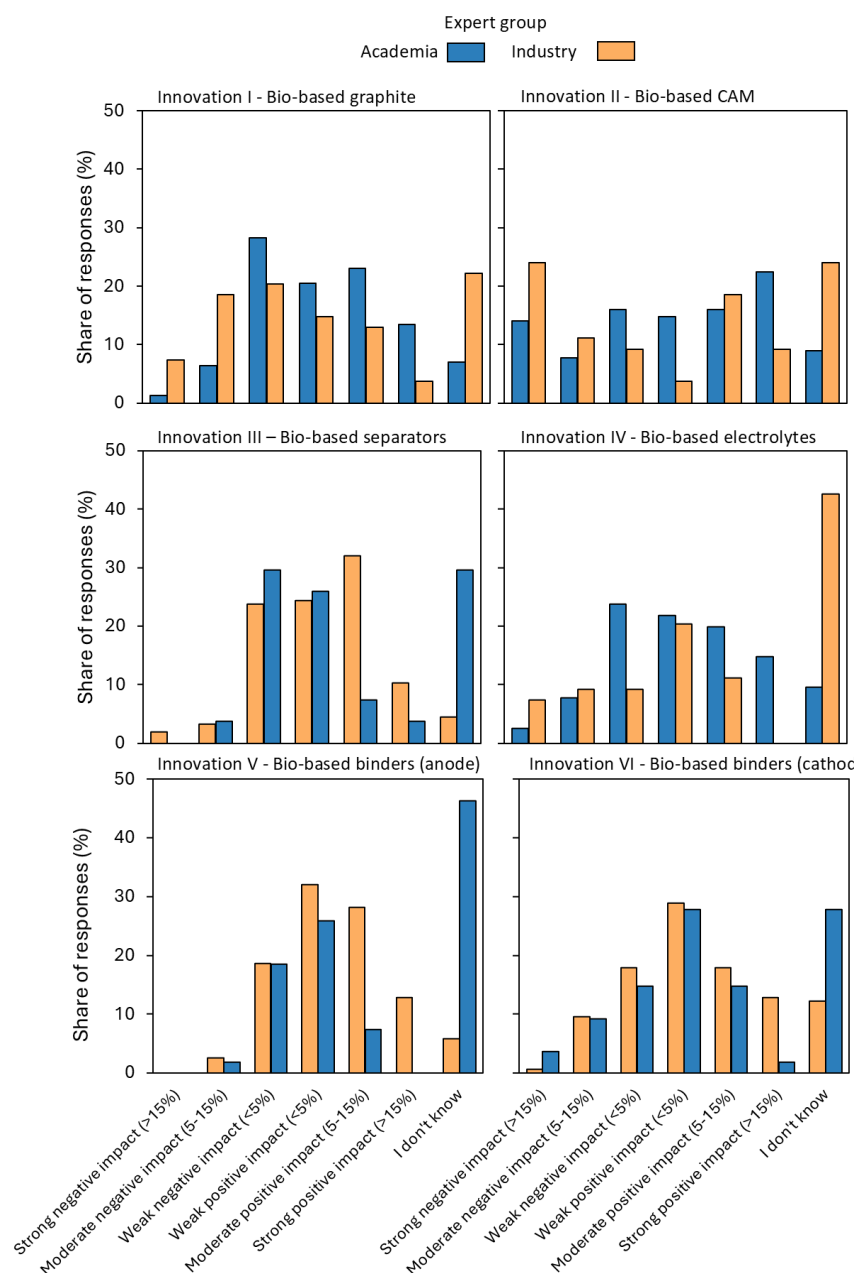


Figure 3. Role split normalized impact response distributions (Academia vs Industry).

4. Discussion and Outlook

Our results identify a clear asymmetry in expert expectations. Bio-based battery innovations were primarily valued for prospective reductions in carbon emissions, material costs, and end-of-life burdens, while their principal perceived liabilities concerned specific energy and lifetime. This finding has a straightforward but important implication: renewable material origin alone is an inadequate criterion

for research prioritization. A material that reduces production emissions but shortens battery lifespan may increase replacement frequency and offset part—or conceivably all—of its initial environmental advantage. Likewise, improved recyclability offers limited system-level benefit if lower energy density increases material requirements per unit of delivered storage.

The dimensions assessed here are increasingly regulatory as well as technical criteria, as the EU

Batteries Regulation (see European Union, 2023), currently the most comprehensive framework of its kind, illustrates (Carratta, 2025). First, the Batteries Regulation requires carbon footprint declarations and foresees performance classes and maximum thresholds for electric-vehicle, light-means-of-transport and larger rechargeable industrial batteries (Art. 7). Because the carbon footprint is expressed per kWh of total energy delivered over the battery's expected service life, the emission reductions experts anticipated will count in regulatory terms only if they are not eroded by the specific-energy and lifetime penalties experts also expected. Second, the Regulation introduces minimum performance and durability requirements (Art. 10), so that lifetime penalties become a question not only of competitiveness but potentially of market access. Third, recycling targets and recycled-content obligations (Arts. 8 and 71) reward the recovery of specific metals, to which bio-based binders, separators and electrolytes contribute little (Schlehuber et al., 2026). As comparable requirements emerge in other jurisdictions, research prioritization should consider not only expected technical and environmental performance but also how each innovation would fare under the regulatory metrics that govern market entry.

At the technical level, research programs should therefore evaluate bio-based components at cell and lifecycle levels rather than treating component substitution as an isolated materials problem. For relatively mature pathways such as bio-based anode binders, bio-based separators, or bio-based graphite the next step should be comparative testing against a clearly specified conventional benchmark, accompanied by prospective lifecycle and techno-economic assessment. Critical outcomes include energy and power density, degradation, safety, manufacturing yield, feedstock variability, energy demand, and recovery efficiency. For less mature pathways, funding should focus on resolving the mechanisms underlying the anticipated performance penalties.

The findings also support a portfolio rather than winner-takes-all funding strategy. Near-term investment can prioritize pathways combining environmental benefit, manageable performance risk, and expected maturity within ten years. Longer-term funding should preserve potentially transformative concepts whose present

technical limitations may be addressed through hybrid materials, protective interfaces, electrode architecture, or cell-level redesign. Figure 1 should consequently be used to formulate research questions, not to terminate work on low-ranked innovations.

However, several limitations warrant a cautious interpretation of the results. First, 35 participants are sufficient for an exploratory elicitation but not for representative estimates of a heterogeneous global expert community. The sample was dominated by academics, and recruitment may have introduced professional, geographic, or network selection bias. Second, expertise was represented only through broad occupational categories; future surveys should document disciplinary specialization, years of experience, battery component expertise, and familiarity with each innovation. Third, respondents assessed short innovation descriptions rather than standardized technical specifications. Differences in assumed feedstocks, processing routes, system boundaries, or reference technologies may therefore explain part of the observed variation. Fourth, the response categories combine direction and approximate percentage magnitude, but respondents may not have applied those thresholds consistently. Fifth, the ordered-score ranking depends on an arbitrary numerical mapping. The number of evaluated responses is further decreased by the exclusion of the "I don't know" answers from the ordered-score ranking. Finally, elicited expectations are hypotheses, not empirical demonstrations of sustainability performance.

Despite these limitations, the survey offers a useful early-stage diagnosis. Experts consistently identified environmental opportunities but were unwilling to assume that bio-based materials would preserve battery performance. Innovation V, bio-based anode binders, emerged as the most balanced candidate under the exploratory comparison, whereas Innovation II, bio-based CAM, requires particular attention to specific energy and lifetime. The immediate priority is not to declare a universal winner, but to convert these judgments into testable comparisons. Coordinated electrochemical testing, lifecycle assessment, techno-economic analysis and pilot manufacturing can determine whether the anticipated environmental gains survive real-world performance constraints.

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Statement of AI Usage

Generative artificial intelligence (AI) tools were used solely for language editing and manuscript refinement. All scientific content, analyses, interpretations, and conclusions remain the sole responsibility of the authors.

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Appendix : BIOSTORE Expert Survey Questionnaire

Assessing the potential of bio-advanced battery innovations

Dear participant,

we invite you to share your expertise by taking part in this 10-minute survey. The aim of the survey is to find out how a set of battery innovations could potentially impact performance, costs and environmental impacts.

As a reference point, we define the status quo as an **NMC811-graphite lithium-ion battery cell** with ethylene carbonate (EC) and ethyl methyl carbonate (EMC) in a 3:7 ratio as electrolyte containing 1M LiPF₆, and a polypropylene/polyethylene (PP/PE) separator produced on an industrial scale. On the cathode side, polyvinylidene fluoride (PVDF) is used as a binder and *N*-methyl-2-pyrrolidone (NMP) as a processing solvent, while on the anode side, carboxymethyl cellulose/styrene-butadiene rubber (CMC/SBR) and water are used.

This reference cell has the following baseline values:

Specific energy: 0.25 kWh/kg

Cost: \$120 per kWh

Carbon footprint: 80 kg CO₂-eq per kWh

In the survey, each of these values is set at 100%, and you will be asked to estimate how different innovations compare to this baseline in terms several parameters. In this context, a **positive** impact is defined as an **increase** in specific energy, lifetime/cycling, and recycling capability, as well as a **decrease** in costs and carbon footprint. A **negative** impact is the opposite of this.

The survey is structured so that you answer the same questions for each innovation option, followed by some general questions about the innovations and about yourself to enable comparison.

Thank you for supporting our research!

The BIOSTORE-Team

* Erforderlich

Privacy Notice - GDPR Compliance

As part of our research project at the University of Münster, we are conducting a survey to gather data for academic purposes. This privacy notice is intended to inform you, in accordance with the General Data Protection Regulation (EU) 2016/679 (GDPR), about how your personal data will be processed.

Who is responsible for your data?

The data controller for this research project is the University of Münster, represented by the BIOSTORE Team. For any questions, you can contact us at biostore@uni-muenster.de.

Purpose of data collection

Your responses will be used solely for academic research purposes. The data collected will help us evaluate the opportunities and trade-offs of integrating new, nature-based components into established battery systems.

Legal basis for processing

Your participation is entirely voluntary. By agreeing to take part in this survey, you provide your informed consent for us to collect and process your data under Article 6(1)(a) GDPR.

What data we collect

The survey may collect the following:

- Anonymous responses to research questions
- Demographic data such as age, gender, or education level
- No personally identifiable data will be collected unless explicitly stated and consented to

Data storage and protection

All data will be securely stored on encrypted and password-protected systems. Only authorized members of the research team will have access to the data. No data will be shared with third parties or used for commercial purposes.

Data retention

Your data will be retained only as long as necessary to fulfill the research purpose and will be anonymized or deleted upon publication of the results.

Your rights

Under GDPR, you have the right to:

- Withdraw your consent at any time without consequences
- Access your data
- Request rectification or erasure
- Restrict or object to processing
- Lodge a complaint with a supervisory authority (e.g., the German Data Protection Authority)

Contact for data protection concerns

If you have questions about how your data is used, please contact Nina Meyer-Pachur, at nina.meyer-pachur@uni-muenster.de.

Innovation I: Bio-based Graphite

Bio-based graphite is an alternative to conventional graphite used in lithium-ion batteries. Unlike traditional graphite sourced from fossil resources, biobased graphite is derived from renewable biomass, such as vegetable carbon (biochar). This material aims to reduce environmental impact while offering comparable performance.

1. How do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

2. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ > 10 years
- ☐ Never
- ☐ I don't know

3. If possible, could you please elaborate on this?

Innovation II: Bio-based/Organic Cathode Active Material

Bio-based cathode active materials are innovative alternatives to conventional metal-based cathodes in lithium-ion batteries. Instead of relying on mined metals like cobalt or nickel, these materials utilize organic compounds derived from renewable biomass sources. They aim to reduce dependence on critical raw materials while providing stable electrochemical performance and improved environmental sustainability.

4. How do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

5. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ >10 years
- ☐ Never
- ☐ I don't know

6. If possible, could you please elaborate on this?

Innovation III: Bio-based Separators

Bio-based separators are a novel alternative to conventional battery separators made from fossil-derived polymers such as polyethylene (PE). These innovative materials are produced from renewable sources such as polysaccharides (e.g., cellulose or chitosan). They aim to maintain or improve battery safety and performance while reducing environmental impact and dependence on fossil resources.

7. How do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

8. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ >10 years
- ☐ Never
- ☐ I don't know

9. If possible, could you please elaborate on this?

Innovation IV: Bio-based Electrolytes

Bio-based electrolytes represent an emerging class of electrolyte solvents designed to replace conventional fossil-derived mixtures such as ethylene carbonate (EC) and ethyl methyl carbonate (EMC) in lithium-ion batteries. These alternatives are derived from renewable feedstocks and aim to match or exceed the electrochemical stability, ionic conductivity, and safety performance of standard solvents. The substitution may influence overall system performance, cost structures, and environmental impact.

10. How do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

11. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ >10 years
- ☐ Never
- ☐ I don't know

12. If possible, could you please elaborate on this?

Innovation V: Bio-based Binders

Bio-based binders serve as renewable alternatives to traditional polymer binders in lithium-ion batteries. Sourced from natural materials such as polysaccharides (starch, alginate) or lignin, these binders aim for strong adhesion of active materials to current collectors while maintaining flexibility and conductivity. By replacing petroleum-derived binders, they contribute to greener and more sustainable battery manufacturing.

The type of binder also affects the processing of electrodes. As this can differ for anodes and cathodes, the answers to the questions below are separated in anode and cathode side. Please answer the questions for both electrodes.

13. In terms of the **anode**, how do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

14. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ > 10 years
- ☐ Never
- ☐ I don't know

15. In terms of the **cathode**, how do you think will this innovation impact the cell's... *

	Strong negative impact (> 15%)	Moderate negative impact (5- 15%)	Weak negative impact (<5%)	Weak positive impact (<5%)	Moderate positive impact (5- 15%)	Strong positive impact (> 15%)	I don't know
Specific Energy	☐	☐	☐	☐	☐	☐	☐
Lifetime/Cycling	☐	☐	☐	☐	☐	☐	☐
Material Cost	☐	☐	☐	☐	☐	☐	☐
Production Cost	☐	☐	☐	☐	☐	☐	☐
Carbon Footprint	☐	☐	☐	☐	☐	☐	☐
Recycling Capability	☐	☐	☐	☐	☐	☐	☐

16. How long do you think would it take for this innovation to be successfully introduced to the market (lab-research + scale-up)? *

- ☐ <5 years
- ☐ 5-10 years
- ☐ > 10 years
- ☐ Never
- ☐ I don't know

17. If possible, could you please elaborate on this?

General questions about these innovations

18. How likely are you to be willing to pay up to 20% more for a bio-based LIB? *

0	1	2	3	4	5	6	7	8	9	10
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Not at all likely

Extremely likely

19. Can you give reasons for your choice above? *

20. Among the innovations described, which two have the greatest potential for industry? *

Wählen Sie 2 Optionen aus.

- ☐ Innovation I: Bio-based Graphite
- ☐ Innovation II: Bio-based/Organic Cathode Active Material
- ☐ Innovation III: Bio-based Separators
- ☐ Innovation IV: Bio-based Electrolytes
- ☐ Innovation V: Bio-based Binders

21. Can you explain your choice above in one sentence? *

22. How will the above innovations impact recycling? *

23. What is the most promising innovation for the next five years? Did we overlook any potential innovations in this field? *

About you

Finally, here are some last questions about yourself

24. What is your highest degree? *

- ☐ Apprenticeship
- ☐ Bachelor
- ☐ Master/Diploma
- ☐ PhD
- ☐ Sonstiges

25. What is your scientific background? *

- ☐ Natural Sciences
- ☐ Engineering
- ☐ Social Sciences
- ☐ Humanities
- ☐ Sonstiges

26. In which sector are you currently working? *

- ☐ Academia
- ☐ Industry
- ☐ Sonstiges

27. Based on your answer above, which sub-sector would you classify yourself in? *

28. How many years of experience do you have in your field? *

- ☐ <5 years
- ☐ 5 - 10 years
- ☐ 10 - 15 years
- ☐ 15 - 20 years
- ☐ >20 years

29. What age group do you belong to? *

- ☐ 18 - 25
- ☐ 26 - 35
- ☐ 36 - 45
- ☐ 46 - 55
- ☐ >55

30. Which gender do you identify with? *

- ☐ Male
- ☐ Female
- ☐ Non-Binary
- ☐ Prefer not to say
- ☐ Sonstiges

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 Microsoft Forms

Research Paper

Maria Nero^a, Sandra Gröne^b

Robustness Maps: A Scenario-Based Framework for Strategic Feedstock Sourcing under Uncertainty

Manufacturers sourcing bio-based, synthetic, and mineral feedstocks face growing uncertainty from regulatory change, climate impacts, and market volatility. Existing approaches, including scenario planning and quantitative optimization, remain loosely coupled and offer limited support for assessing robustness at the level of strategic performance indicators.

This study develops a scenario-based robustness diagnostics framework linking exogenous context drivers, endogenous feedstock dynamics, and Future Performance Indicators (FPIs) within a transparent, semi-quantitative analytical logic. The framework introduces robustness maps, which visualize FPIs, such as demand, availability, price, and carbon footprint, by their expected trend and scenario-dependent volatility across time horizons.

A palm kernel oil case study demonstrates the framework's application, showing how it can identify system vulnerabilities and inform long-term sourcing strategy. By bridging qualitative foresight and performance-based diagnostics, the framework provides a transferable approach for assessing feedstock robustness and supporting resilient raw-material strategies in the chemical industry and beyond.

Keywords: Robustness diagnostics, Scenario analysis, Feedstock sourcing, Robustness mapping, Foresight analytics, Raw material strategy.

1. Introduction

The global chemical industry is undergoing a fundamental transformation to its resource base. Raw material sourcing is expanding from today's fossil and mineral feedstocks to include bio-based, recycled, and CO₂-derived supply systems (von Vacano et al., 2026). This shift coincides with a period of high uncertainty in supply chains (Roscoe et al., 2022; Kanacs, 2023). The global nature of many of today's supply chains can enable cost savings, but also exposes those involved to the risks of a global footprint. Recent geopolitical disruptions, such as the Russia-Ukraine war, crises in the Red Sea and Strait of Hormuz, and the US-China trade

war are putting pressure on global supply chains, and the disruption risks extend beyond geopolitics. Evolving natural disasters and extreme weather, infrastructure disruptions, changing regulation, and pandemics create further uncertainty (WEF, 2026; OECD, 2025), compounding the inherent uncertainty of sourcing itself: e.g., in demand, yields, feedstock availability, and price (Applequist et al., 2000).

Feedstock decisions are business critical and have long-lasting implications in the chemical industry. They directly influence production costs and environmental

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performance, and uncertainties can lead to material shortages, production stops, and economic losses. Creation or modification of chemical production assets typically requires significant planning and capital investments, and the resulting assets have planned operational lifetimes spanning several decades (Applequist et al., 2000; Seto et al., 2016). Because established supplier networks and supply chain structures can be difficult to change due to scarcity or entrenchment, organizations tend to develop decision-making logics that reinforce existing configurations and align with those of their industry peers (Roscoe et al., 2022). As with carbon lock-in, increasing returns can prevent transitions and inhibit innovation (Janipour et al., 2020). Today's feedstock and technology choices therefore shape strategic trajectories far into the future, requiring simultaneous consideration of economic, environmental, and supply-related objectives, where a vulnerability in one dimension can undermine overall system performance. For bio-based feedstocks such as palm kernel oil (PKO), the raw material explored in this chemical industry case study, uncertainties can manifest as volatile prices, supply disruptions, shifting environmental requirements, and resulting demand swings (Nair et al., 2024). Regulatory uncertainty is particularly acute for PKO: companies selling palm-based products in the EU must show that their supply chain is deforestation-free under the EU Deforestation Regulation (EUDR) from December 2026, an implementation timeline already twice postponed, from 2023 to 2025 to late 2026 (European Union, 2023).

In supply chain risk management literature low-frequency disruption risks are distinguished from everyday operational uncertainties (Tang, 2006) and resilience is defined as the capacity to prepare for, respond to, and recover from disruptions while maintaining continuity of operations (Ponomarov and Holcomb, 2009; Christopher and Peck, 2004). Robustness, as used in this study, is related but distinct: it describes consistent performance across a range of plausible futures, independent of any single disruption. In uncertain environments, relying on a single forecast or scenario can be akin to making a bet, as the underlying assumptions may themselves become increasingly uncertain. In the terms proposed by Courtney et al. (1997), decision-makers often face high levels of strategic uncertainty for which single-point forecasts

are not reliable, warranting a broader analytical toolkit. Robustness analysis supports making better decisions by considering multiple plausible futures (Maier et al., 2016; Kanacs, 2023), rather than making better predictions (Lempert, 2019). Strategies (or in this case, feedstocks) performing at least satisfactorily across scenarios are "robust". The decision-making-under-deep-uncertainty (DMDU) literature has developed a range of formal metrics which operationalize this, including expected-value, higher-order-moment, regret-based, and satisficing metrics (Wald, 1950; Kwakkel et al., 2016; Savage, 1950; Simon, 1956). Comparative studies show that the choice of metric can itself change which alternative ranks best (Herman et al., 2015; Lempert and Collins, 2007; McPhail et al., 2018). The robustness maps developed here adopt a trend-and-dispersion approach conceptually closest to variance-based metrics, but with volatility as the primary risk signal. Section 2 develops this logic in detail.

Two dominant paradigms have emerged for managing uncertainty in strategic sourcing: strategic foresight, particularly scenario planning, and quantitative robust optimization. Strategic foresight and scenario planning should use information of strategic significance to identify emerging risks, opportunities, and potential tipping points (Rohrbeck and Kum, 2018; Wack, 1985), and provide structured narratives of plausible alternative futures and the underlying forces leading there (Schoemaker, 1995; Wilkinson and Eidinow, 2008). Scenario planning has been integrated into supply chain planning to enhance resilience and adaptability (Sardesai et al., 2021), typically structured around STEEP (societal, technological, ecological, economic, political) dimensions (Morrison and Wilson, 1996; Markley, 2011). Its central weakness, identified by Wack (1985) and still unresolved, is the interface between scenarios and decision-makers: without a rigorous link to performance metrics, scenario narratives risk being treated as plausible stories rather than actionable strategic data.

Robust optimization and stochastic programming provide a quantitative counterpart, differing from scenario planning in being heavily grounded in mathematics while serving the same purpose of supporting decisions under uncertainty (Maggioni et al., 2017). Stochastic programming assigns probabilities to scenarios and aims to identify solutions that perform

best on average (Santoso et al., 2005), but for long-term horizons such as the one considered in this study (up to 2050), probability estimates become unreliable. Robust optimization instead allows parameters to vary within defined bounds, prioritizing solutions that perform satisfactorily across all futures and are less vulnerable to extreme events (Bertsimas et al., 2011; Pishvaei et al., 2011). These approaches have been applied to the chemical industry, where volatility in raw-material costs, product prices, process yields, and market demand can substantially alter the relative attractiveness of alternative sourcing configurations (Al-Qahtani et al., 2008). Both stochastic programming and robust optimization are decision-focused and mathematically rigorous, but their outputs are often difficult for non-specialists to interpret and communicate, even though well-structured decision aids matter for decision-makers' success (Lempert, 2019). Further, they offer limited insight into the causal mechanisms driving robustness.

Although numerous methods exist for assessing uncertainty and robustness, the resulting insights are often insufficiently transparent, diagnostic, and transferable for strategic feedstock decision-making. Three limitations stand out. First, qualitative scenario narratives and quantitative assessments are often treated as loosely coupled steps, if not separate activities (Rezaei et al., 2020), giving practitioners little visibility into how qualitative drivers (e.g., supply chain stability) propagate through a feedstock system to influence quantitative indicators (e.g., PKO price). Second, existing approaches typically focus on identifying robust or optimal outcomes, but offer limited visibility into the causal mechanisms generating them, leaving decision-makers without accessible decision aids at the level of concrete key performance indicators—termed Future Performance Indicators (FPIs) in this paper—such as demand, price, availability, and CO₂ footprint—even though visual tools for exploring and communicating uncertainty are increasingly recognized as important (Hadjimichael et al., 2024; Shavazipour et al., 2021). Third, existing contributions typically focus on specific sectors, modelling architectures, or decision contexts, lacking a generic, cross-sector framework that enables consistent comparison across bio-based, synthetic, and mineral feedstocks.

Guided by these considerations, the paper addresses the core research question: How can scenario-based robustness of raw material sourcing be represented and analyzed to bridge the gap between qualitative foresight and quantitative strategic indicators? Specifically, the paper develops a framework that (i) integrates qualitative external drivers and quantitative FPIs, (ii) provides practitioners with transparent, visual diagnostics of robustness for deriving actionable insights in sourcing and technology roadmapping and (iii) is widely applicable across sectors and technologies. Its primary contribution is the introduction of robustness maps, a visualization tool that translates complex system variability into an accessible common robustness language, demonstrated through a PKO case study that shows how the framework can inform diversification strategies and resilient raw material management under deep uncertainty.

Building on and extending prior work on robust supply chain optimization and scenario-based planning, the framework is designed to be methodologically neutral with respect to the underlying models while providing a common robustness “language” across sectors. Robustness maps bear a superficial resemblance to established two-dimensional risk-visualization tools, such as the probability-impact matrix in enterprise risk management standards (ISO, 2018) and portfolio-positioning tools like the growth-share matrix (Henderson, 1970), but differ in three ways. First, probability-impact matrices plot the likelihood of a risk event against its consequences, whereas robustness maps plot the expected direction of change of a performance indicator against its volatility across a scenario set, focusing on trajectory rather than occurrence. Second, portfolio matrices position business units or products relative to one another on largely static, or single-period measures, while robustness maps track a set of FPIs across multiple future time horizons. Third, each point on a robustness map is derived from the paper's approach linking exogenous context drivers to endogenous feedstock dynamics (Section 2), giving it a traceable path back to specific scenario assumptions, which is typically not offered by conventional risk and portfolio matrices based on often unstructured expert judgement.

The remainder of this paper is organized as follows. Section 2 introduces the conceptual framework and its operational logic, with full methodological detail provided in the Methods Appendix. Section 3 applies the framework to the PKO case study, illustrating how the semi-quantitative logic handles real-world volatility in the chemical supply chain. Section 4 discusses strategic implications for Business Chemistry, the framework's transferability to other resource-intensive sectors, its limitations, directions for future research, and closes with a concluding summary.

2. Conceptual Framework and Methodology

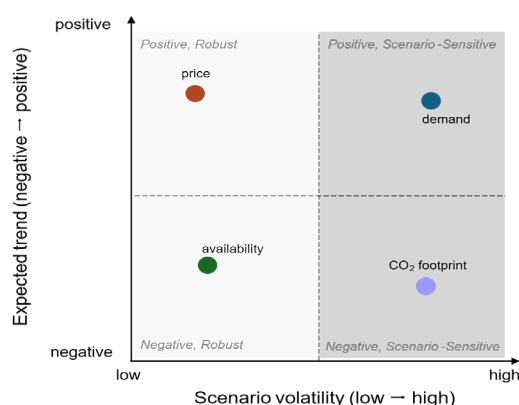
This section introduces the proposed framework for scenario-based robustness diagnostics. The framework is designed as a generic, feedstock-agnostic approach to support strategic decision-making under uncertainty in raw material sourcing. Rather than predicting outcomes or optimizing for a single expected future, it makes

robustness transparent at the level of strategically relevant performance indicators, treating robustness as an emergent property of how key performance dimensions behave across structurally different future contexts. The framework is presented starting from its diagnostic output, robustness maps, before tracing the underlying analytical structure that produces them; full methodological detail, formulas, calibration procedures, and a worked example are provided in the Methods Appendix (Section 6).

2.1 Robustness Maps

Robustness maps are the framework's central analytical interface, capturing uncertainty and directional trend in a single representation (Figure 1). Each Future Performance Indicator (FPI) is positioned in a two-dimensional space defined by its expected directional development (vertical axis, negative to positive trend) and the dispersion of its outcomes across scenarios (horizontal axis, low to high volatility). A boundary along the volatility axis separates robust from scenario-sensitive regions and a boundary along the x-axis

(a) Static robustness map (T2)



(b) Dynamic extension (T0 → T1 → T2)

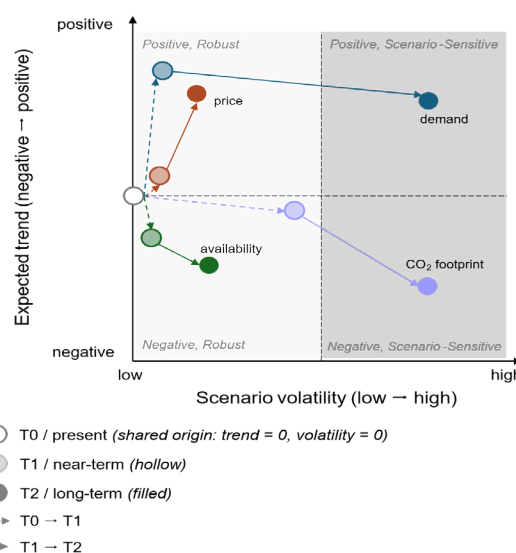


Figure 1. Stylized robustness maps (a) Static representation showing each performance indicator's long-term (T2) position, and (b) dynamic extension tracing indicator development from a shared present-day origin (T0, trend = 0, volatility = 0) through a near-term horizon (T1) to the long-term horizon (T2, matching panel a). Positions are plotted by expected trend (vertical axis) against scenario volatility (horizontal axis, low to high). The robust/scenario-sensitive boundary is shown here as an equal partition for illustrative neutrality; in applied use, this boundary should be calibrated to the case at hand (e.g., empirically or via a substantive threshold). The figure is illustrative and does not refer to a specific feedstock system.

separates these into positive and negative directional regions; the Methods Appendix details the available calibration approaches. In the static representation (Figure 1a), each FPI appears as a single point at the long-term horizon; the dynamic representation (Figure 1b) traces its position from a shared present-day origin (T0) at which point, by definition, no directional trend or scenario divergence has yet materialized, through a near-term (T1) to a long-term (T2) horizon, making visible whether an indicator's robustness profile shifts over time—a strategically significant signal given the chemical industry's long investment cycles. Robustness maps thus support strategic considerations regarding timing, emerging risks, and adaptation pathways. Importantly, robustness maps are not predictive tools. They function as diagnostic representations that make uncertainty structures visible and comparable.

2.2 Future Performance Indicators (FPIs)

FPIs are strategically relevant outcome dimensions, such as demand, price, availability, or environmental performance, which are selected *ex ante* against three criteria: materiality for the sourcing decision, availability of reliable directional assessments across scenarios, and interpretability for non-technical audiences. While the specific selection may vary, FPIs provide a consistent reference frame for comparing robustness across alternative feedstocks and sourcing strategies. FPIs are diagnostic indicators, emphasizing directional insight over numerical precision, allowing the framework to remain applicable in contexts where detailed modeling is not feasible. FPIs are typically interdependent, as shown in Figure 3, and trade-offs remain explicit. This multi-dimensional view is particularly relevant in the chemical industry, where strategic decisions involve balancing economic, operational, and environmental objectives.

2.3 Endogenous Feedstock Drivers

Each FPI's behavior is shaped by endogenous feedstock drivers, which represent the internal structure of a feedstock system and transmit external development context into performance outcomes. Drivers are partially controllable, interdependent, and often affect multiple FPIs simultaneously. These relationships are captured through transparent linkages rather than explicit modeling to maintain interpretability. The use of endogenous drivers provides two key benefits: (i)

traceability, linking FPI outcomes to underlying system mechanisms and thereby addressing the translation-logic gap identified in the introduction, and (ii) actionability, highlighting where strategic interventions may influence robustness.

2.4 Exogenous Context Drivers and Scenarios

Exogenous context drivers define the boundary conditions under which feedstock systems operate (e.g., geopolitical dynamics, technological change, climate-related impacts). They are typically identified using a STEEP scan (societal, technological, ecological, economic, political), a structured categorization scheme widely used in strategic foresight to systematically identify weak signals and emerging risks or opportunities across an organization's external environment (Morrison and Wilson, 1996; Markley, 2011). The exogenous context drivers are identified and assessed in each of a set of scenarios, on their directional development over the relevant time horizons. Together, exogenous context drivers and scenarios define the uncertainty space within which system behavior is explored, thereby defining the starting point for the analytical process by specifying how external conditions are expected to evolve. The framework is compatible with existing sector-specific foresight studies as a source of scenarios and does not require entire new development of scenario sets.

2.5 Operationalization and Analytical Logic

The framework proceeds bottom-up (Figure 2): exogenous context drivers are assessed per scenario and horizon on a standardized directional scale indicating whether it is expected to increase, decrease, or remain stable; these developments are translated into scenario-specific endogenous driver developments; driver developments are aggregated, using expert-informed weights; and the trend and dispersion values are calculated to position each FPI on the robustness map, illustrating expected trends and dispersion across scenarios and evolution of robustness over time. This propagation logic draws on causal loop and influence diagrams from System Dynamics (Sterman, 2000; Forrester, 1961), which has demonstrated applicability to chemical-industry disruption dynamics (Gröne et al., 2019), but deliberately omits closed feedback loops and simulation in favor of a one-pass structure that prioritizes

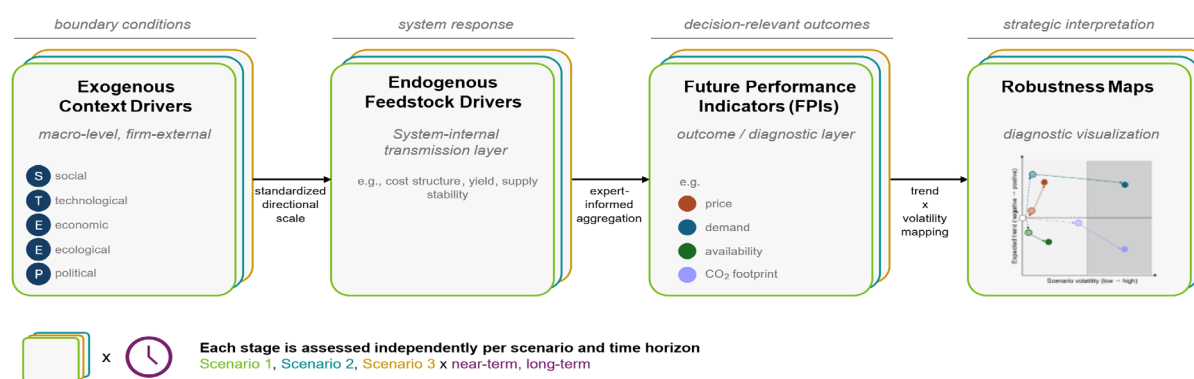


Figure 2. Schematic overview of the robustness diagnostics framework. Linking exogeneous context drivers, endogenous feedstock drivers, and Future Performance Indicators to robustness maps. Stacked outlines indicate that each stage is assessed independently across scenarios and time horizons. The figure is illustrative and does not refer to a specific feedstock system.

managerial interpretability over dynamic completeness (see Section 4.3). The Methods Appendix reproduces this logic step by step, including a worked numerical example using Global PKO Availability from Section 3, showing exactly how driver scores translate into an FPI's trend and dispersion coordinates. This stepwise propagation ensures full traceability, allowing users to understand how systems perform and why outcomes emerge. By combining scenario analysis, structured system representation, and intuitive visualization, the framework provides a practical diagnostics tool for assessing feedstock robustness under deep uncertainty.

3. Palm Kernel Oil Case Study

To demonstrate the applicability of the proposed scenario-robustness framework, the methodology was applied to the case of global PKO sourcing as a future feedstock option for the specialty chemical industry. Bio-based feedstocks are important as substitutes for fossil-based feedstocks at the beginning of value chains or as starting points of their own value chains, as in the case of PKO (von Vacano et al., 2026). PKO and palm oil both come from the oil palm. Palm oil is produced via the fleshy mesocarp and palm kernel oil via the hard kernel of the oil palm (S&P Global, 2025a). PKO represents a strategically relevant renewable feedstock in the specialty chemical industry. Owing to its high content of lauric (C_{12}) and myristic (C_{14}) fatty acids, PKO is widely used to produce fatty acids, fatty alcohols, fatty methyl esters, and other oleochemical intermediates. Coconut oil is the only other natural oil

with a comparable composition of lauric oils, making these two not easily substitutable in food and non-food uses (S&P Global, 2025b).

Indonesia and Malaysia are the largest producers of PKO globally, in 2025 producing 8,003,000 metric tons (S&P Global, 2025a). Production is highly geographically concentrated, with over 85% produced in Southeast Asia. Germany is the largest importer and consumer of PKO in Europe. However, exports to Europe from Southeast Asia have declined significantly in recent years. This is in part due to health trends and concern over the high levels of saturated fats in PKO, and also to do with sustainability concerns, as oil palms are linked with deforestation and indirect land use change (S&P Global, 2025a). But at the global scale, consumption is increasing with the expansion of the oleochemical industry. PKO is also highly exposed to regulatory uncertainties, such as the EU Deforestation Regulation, which prohibits import of PKO from deforested land into the EU (European Union, 2023), and the Renewable Energy Directives, which classify PKO as high indirect land-use change risk and caps their contribution to national renewable energy targets via biofuels (European Commission, 2019). PKO is also a first-generation biomass oil crop, scaled for food and feed, and bringing into question topics such as the food versus fuel debate. The future availability, demand, price, and environmental performance of PKO are shaped by the interacting pressures of demand growth, sustainability challenges, climate change impacts, regulation, supply chain stability, and food

security among others.

Evonik AG is a purchaser of fatty alcohols on the basis of PKO. Fatty alcohols can be produced from renewable raw materials such as oils and fats or from petrochemical sources. Fatty alcohols, such as lauryl alcohol (C12) are used to manufacture surfactants for detergents, household cleaners, personal care products, shampoos, and cosmetics. An estimated 101,000 metric tons of fatty acids were consumed in the production of fatty alcohols in Western Europe in 2025 and this is expected to grow at a CAGR of 2% till 2029 (S&P Global, 2025b). PKO-derived lauric acid and fatty alcohols are also important building blocks for emulsifiers, lubricants, amines, quaternary ammonium compounds, and other specialty chemicals. Due to its high yield of C12-C14 carbon chains, PKO is particularly well suited for surfactant manufacture and remains one of the dominant renewable feedstocks for detergent-range oleochemicals worldwide. As a result, its long-term availability and resilience have strategic implications for multiple downstream industries, including home care, personal care, industrial cleaning, and specialty chemicals.

Due to the strategic importance of PKO in specialty chemicals, colleagues from research, development, and innovation (RDI), procurement, various business lines, and external interview partners were included in the analysis of the future PKO landscape. The case study illustrates how qualitative scenario analysis can be translated into structured robustness insights for strategic raw material sourcing by systematically linking exogenous context factors to feedstock-specific system characteristics and, ultimately, to decision-relevant performance indicators through robustness maps.

3.1 Applying the Framework to PKO

The PKO assessment follows the previously introduced robustness framework. At the most aggregated level, four FPIs were defined: global PKO demand, global PKO availability, PKO carbon footprint, and PKO purchase price. These indicators capture the central dimensions of feedstock viability for industrial users: market pull, physical accessibility, environmental pressure, and procurement cost. Similar to other robustness-oriented studies, the aim was not to identify a single “best” future (Lempert, 2019), but to assess whether PKO remains

strategically robust across multiple plausible futures.

Each FPI was then decomposed into the endogenous feedstock drivers. The feedstock drivers are the internal drivers specific to the raw material system that exert major influence on the PKO system and therefore the trajectory of the FPI. For example, for global PKO availability, these included total plantation area, fresh fruit bunch yield per hectare, PKO extraction potential, and domestic supply chain stability.

Each feedstock driver was explored in a dedicated deep dive to establish its current state and its future development potential. This decomposition allowed the analysis to connect high-level FPI behavior to the operational and structural factors that shape it. Through the deep dives on the feedstock drivers, the exogenous context drivers were identified. For the example of total plantation area, this included drivers such as climate-induced land loss, land-use regulation, investment conditions for agricultural expansion, competition for land, technological innovation in breeding and cultivation, and others.

Through the FPI, endogenous feedstock driver, and exogenous context driver logic, a transparent linkage from the macro-level uncertainties to the feedstock-specific drivers was established. A systems thinking approach was adopted to synthesize these insights and illustrate the interactions and interdependencies in a comprehensive representation of the PKO system (see Figure 3).

3.2 Scenario Selection

Once the exogenous context drivers were established, these were evaluated against a set of three pre-existing scenarios. These scenarios are drawn from an externally published global scenario set, the *Future(s) of the Specialty Chemical Industry*, which describes five plausible futures for the specialty chemicals industry up to 2040 and was developed in a separate foresight exercise. Three of these five scenarios, Sustainability Paradigm, Deceptive Calm, and Turbulent Times, were selected for the present PKO analysis. Of the two scenarios not selected, Digital Champions, centered on the growing influence of digital platforms and technology-driven disruption of value chains, was excluded because its primary drivers were assessed

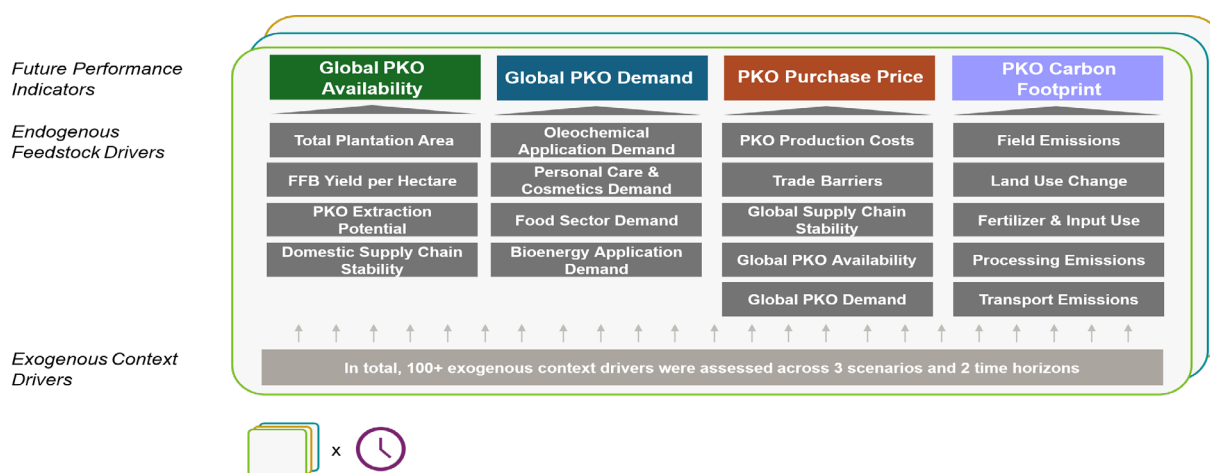


Figure 3. System overview of the palm kernel oil (PKO) feedstock case. The four Future Performance Indicators (FPIs)—global PKO availability, global PKO demand, PKO purchase price, and PKO carbon footprint—are each decomposed into their respective endogenous feedstock drivers, which in turn are shaped by more than 100 exogenous context drivers. The stacked outlines behind each column indicate that both the FPI and its underlying endogenous drivers were assessed independently for each of the three scenarios (Sustainability Paradigm, Deceptive Calm, Turbulent Times) and across both time horizons (2025-2035, 2035-2050).

as having comparatively limited direct bearing on the physical, regulatory, and geopolitical dynamics that most directly shape feedstock availability, price, and sourcing risk. Chinese Dream, centered on China's trajectory toward a dominant, "eco-civilization" role in global affairs, was also excluded: its fast-evolving dynamics were judged to warrant a dedicated, deeper investigation beyond the scope of a global assessment. For this reason, the scenario was examined separately in a China-focused foresight exercise, whose findings may complement the present robustness assessment in future work. The present analysis draws on the published scenario set as its foundation; it does not represent the complete internal decision-making process, which may incorporate additional proprietary considerations not detailed here. Each of the three selected scenarios is briefly characterized below. The Sustainability Paradigm describes a scenario where sustainability has become the guiding economic principle and driver for innovation, initiated by strong regulatory pressures. Digital technologies, breakthroughs in biotechnology, and cheap electricity from renewable sources enable the transformation into a circular bioeconomy. Companies develop a

variety of sustainable solutions to meet the growing demand for green chemicals. The use of fossil raw materials is massively reduced and a circular chemical supply chain is established. Deceptive Calm describes a world that is changing, but slowly and gradually. At first this means stability, strong economic growth, and business-as-usual. The chemical industry profits from this stability, free trade, and growth. But the pressure to change business models, production processes, and raw material bases is low. The search for solutions to major global problems is postponed still further. Eventually the industry faces the consequences of its inactivity. Climate change and the radical measures to mitigate it affect the industry heavily. Turbulent Times is a scenario where globally spreading nationalism is leading to a new era of deglobalization, with global trade wars and increasing protectionism. The liberal world order has been replaced with a conflict-laden multipolar order with less international solidarity, meaning global problems such as climate change are addressed in a piecemeal fashion. The chemical industry is affected heavily by the spiral of tariffs, isolation, and global conflicts. Companies must reconfigure supply chains and localize production to survive.

3.3 Scoring Methodology

Using the given boundary conditions and developments in each scenario, each context driver was analyzed for its own development in these scenarios. The assessment was done using a qualitative scale ranging from strong decrease to strong increase denoted with arrows. Table 1 illustrates this process for the context drivers underlying total plantation area, one of the endogenous drivers of global PKO availability (see Figure 3). Because some exogenous context drivers relate inversely to the respective endogenous feedstock driver, for instance, stronger land-use regulation reduces rather than increases available plantation area, their scores are sign-adjusted prior to weighted aggregation into Table 2.

To enable early identification of divergence and enable transitioning pathways and actions on shorter timeframes, the time horizon of the scenario analysis was divided into two segments, 2025 to 2035 and 2035 to 2050. This division can highlight unstable or non-linear development pathways of factors towards their “end-state” in 2050. Division of the time horizon can also be used to prioritize actions in terms of their urgency, prioritizing actions addressed towards developments

happening in the shorter term and planning activities for developments that will begin in the future.

For each feedstock driver, the direction of change was derived from the combined influence of its underlying context drivers. The directional assessments were then translated into a simple numerical coding scheme, with strong decrease coded as -2, decrease as -1, stable as 0, increase as +1, and strong increase as +2. The feedstock drivers were given a weight according to expert judgment, reflecting their relative importance for the respective FPI. In the PKO availability case, total plantation area carried the highest weight, followed by yield per hectare, PKO extraction potential, and domestic supply chain stability. Weighted aggregation enabled the transition from qualitative scenario interpretation to semi-quantitative robustness evaluation.

3.4 Future Performance Indicator Results

This section presents the resulting robustness profiles for all four FPIs, beginning with global PKO availability as a detailed illustration of the aggregation logic before summarizing the remaining three FPIs and placing all within the robustness maps. Global PKO availability was defined as the total amount of PKO that can be supplied

Table 1. Exogenous context drivers underlying the endogenous feedstock driver “Total Plantation Area” (see Fig. 3), with their expected directional development across scenarios and time horizons. Arrows indicate the expected direction of change per scenario and horizon, coded from strong decrease (↓↓) to strong increase (↑↑).

Endogenous Feedstock Driver: Total Plantation Area		Scenarios					
Exogenous Context Driver	Description	Sustainability Paradigm		Deceptive Calm		Turbulent Times	
		2035	2050	2035	2050	2035	2050
Climate-Driven Land Loss	Climate impacts like flooding, droughts, erosion, and pest outbreaks can degrade or eliminate current production areas – especially in vulnerable lowland tropical zones.	↑	→	↑↑	↑↑	↑↑	↑↑
Agroclimatic Expansion Potential	Climate change may make non-traditional areas suitable for oil palm cultivation (e.g., parts of Africa, Latin America). Expansion might occur where environmental regulation is weaker.	↑	→	↑	↑	↑	↑↑
Land Use Regulations	Environmental laws and zero-deforestation policies restrict plantation expansion, especially into forested or high-biodiversity areas. Certification schemes further raise barriers.	↑	↑↑	→	↑↑	↓	↓
Investment Climate for Land Expansion	Capital availability risk appetite influence how much land is developed, especially in frontier or smallholder-dominated regions.	↓↓	↓↓	↑	↓↓	↑	↑
Land Competition from Other Uses	Competing land demands (food, feed, fuel, conservation) limit oil palm expansion. This is driven by demand patterns and sustainability priorities.	↑	↑	→	↑↑	↑	↑↑
Breeding Innovation & New Cultivation Systems	New strains with lower chilling requirements, drought resistance, or modular plantation systems could open up areas previously unsuitable for oil palm.	↑	↑↑	↑	↑	→	→

Expected Direction of Change: ↑↑ (+2) Strong increase / ↑ (+1) Increase / → (0) Stable / ↓ (-1) Decrease / ↓↓ (-2) Strong decrease

Table 2. Weighted aggregation of endogenous feedstock drivers into the Future Performance Indicator "Global PKO Availability" by scenario and time horizon. Percentages indicate the relative weight of each driver's influence on the FPI, as estimated by foresight and palm kernel oil industry experts. Driver-level arrows show the expected direction of change; parenthetical values show the resulting weighted scenario score per time horizon, aggregated into an overall scenario score and, ultimately, a single aggregated score across all three scenarios (2025-2050).

		Scenarios						
		Sustainability Paradigm		Deceptive Calm		Turbulent Times		
Endogenous Feedstock Drivers	%*	2025-2035	2035-2050	2025-2035	2035-2050	2025-2035	2035-2050	2025-2050
Total Plantation Area	35	↓	→	↑	↓	→	↓	↓
FFB Yield per Hectare	30	↑	↑↑	→	→	↓	↓	→
PKO Extraction Potential	25	→	→	→	↓	→	↓	↓
Domestic Supply Chain Stability	10	↓	↑	↓	↓↓	↓	↓↓	↓↓
Global PKO Availability		→ (-0.2)	↑ (+0.7)	→ (+0.3)	↓ (-0.8)	↓ (-0.4)	↓ (-1.1)	
		↑ (+0.5)		↓ (-0.5)		↓↓ (-1.5)		
		↓ (-0.5)						

* Weighting of the impact of the respective endogenous feedstock drivers on the FPI as estimated by Foresight & palm kernel oil industry experts
Expected Direction of Change: ↑↑ (+2) Strong increase / ↑ (+1) Increase / → (0) Stable / ↓ (-1) Decrease / ↓↓ (-2) Strong decrease

worldwide based on plantation area, yield per hectare, PKO extraction potential, and domestic supply chain stability, and therefore reflects the volume of oil that is realistically accessible in the global market. The results for Global PKO availability illustrate the analytical depth of this approach (see Table 2). In the Sustainability Paradigm scenario, improvements in agricultural practices and technological innovation are offset by structural constraints due to regulatory pressure on plantation area, leading to a stabilization in availability up to 2035, followed by a moderate increase toward 2050 as yield optimization progresses and supply chains become more stable. In contrast, the Deceptive Calm scenario is characterized by limited regulatory pressure, delayed structural adjustments, and delayed but more drastic climate impacts, resulting in stagnating and then declining availability. Under Turbulent Times, the combined effects of climate shocks, geopolitical instability, and supply chain disruptions lead to a pronounced decrease in availability across both time horizons. Despite the differences in paths, the aggregated trend indicates an overall scenario-independent gradual decline in PKO availability over the long term, highlighting structural limitations such as land scarcity and climate exposure.

The same logic was applied to all FPIs. Global PKO

demand showed structural growth in market pull in two scenarios, but strong shocks to demand in the third. PKO purchase price tended toward an increase across all scenarios, suggesting persistent cost pressure and limited prospects for structural relief. PKO carbon footprint showed a mixed trajectory, with significant improvements in two of three scenarios, and significant worsening in the third. Taken together, the results suggest a system in which demand remains roughly stable, supply weakens, sustainability improves, and prices increase.

Beyond the four aggregated FPIs formally tracked in the robustness maps, the underlying scenario assessments also support a complementary regional reading, extracted qualitatively rather than mapped onto the axes of the robustness maps themselves. For each scenario, regional insights were also extracted for Asia, the primary production region, the Americas, a minor production region, and Europe, the import region of interest for this case study. Asia remained the dominant production region in all scenarios, but its production volumes became increasingly unstable under adverse futures. The Americas showed latent production potential when investment frameworks exist, but in two of three scenarios, potential was not fully realized

because of uncertainty and weak investment signals. Europe remained structurally dependent on imports in all cases, implying persistent exposure to external supply disruptions. These regional patterns highlight that PKO availability is not only a global issue, but also a geographically differentiated robustness problem.

All four FPIs were graphically analyzed using the robustness maps (see Figure 4). The performance indicators were plotted to show their scenario-independent direction of change for both 2035 and 2050 and the volatility, or dispersion, of the directions of change for each scenario. The combined future signal map across all FPIs showed that most indicators exhibit relatively clear directional tendencies rather than highly ambiguous outcomes, with all points either falling within the robust quadrants of the matrix or just passing into the scenario-sensitive quadrants. The robust/scenario-sensitive boundary in Figure 4 is set at a volatility of 0.7. This is a substantively defined threshold (see Methods Appendix): a volatility of 1—indicating maximal disagreement in direction across the three scenarios—was judged too high a bar for an indicator to still count as robust, so the boundary set was set below that level to reflect a more realistic standard of cross-scenario consistency.

For brevity in the discussion of Figure 4 that follows, Sustainability Paradigm, Deceptive Calm, and Turbulent

Times are referred to as S1, S2, and S3, respectively. Demand showed initial robust growth, followed by a more scenario-sensitive decrease as biotech alternatives (S1), economic decline (S2 & S3) and trade shocks (S3) emerge. Availability continuously and robustly decreases until 2050 due to decreasing plantation area (all), seed optimization towards palm oil rather than PKO, and supply chain instabilities. The PKO carbon footprint decreases in the long term with stricter regulations and process and agricultural improvements (S1 & S2). The purchase price remains firmly in the robust quadrants and has a strong positive direction of change due to low availability in all scenarios, climate-change induced production disruptions (S2 & S3) and a higher regulatory burden (S1 & S2). The price continues to grow from 2035 to 2050, but weaker than in the first time horizon due to weakened demand. The future PKO landscape shows consistent directional trends across scenarios, suggesting high predictability. The diverse scenario drivers may call for differentiated strategic responses, but the converging FPIs offer a robust basis for planning.

3.5 Implications for PKO Sourcing

The overall result is a robust but unfavorable PKO landscape for future sourcing. The framework shows that PKO is becoming less robust as a feedstock over time because declining availability, rising prices, and growing climate and land-use pressure are not offset

Table 3. Summary of weighted scenario scores for all four Future Performance Indicators (FPIs), by scenario and time horizon. Values are derived through the same weighted aggregation logic illustrated in Table 2 for global palm kernel oil (PKO) availability, applied consistently across demand, availability, carbon footprint, and purchase price. The rightmost column shows the aggregated score across all three scenarios per FPI, covering the full 2025-2050 time horizon.

Future Performance Indicators	Scenarios						
	Sustainability Paradigm		Deceptive Calm		Turbulent Times		2025-2050
	2025-2035	2035-2050	2025-2035	2035-2050	2025-2035	2035-2050	
Global PKO Demand	↑ (+0.6)	→ (+0.3)	↑ (+1.3)	↓ (-0.8)	↓ (-0.5)	↓↓ (-1.8)	→ (-0.3)
Global PKO Availability	→ (-0.2)	↑ (+0.7)	→ (+0.3)	↓ (-0.8)	↓ (-0.4)	↓ (-1.1)	↓ (-0.5)
PKO Carbon Footprint	↓ (-1.0)	↓ (-1.3)	→ (0.0)	↓ (-1.4)	↑ (+1.0)	↑ (+0.4)	↓ (-0.8)
PKO Purchase Price	↑ (+0.6)	→ (0.0)	↑ (+0.6)	↑ (+0.7)	↑ (+0.5)	↑ (+0.6)	↑ (+1.0)

Expected Direction of Change: ↑↑ (+2) Strong increase / ↑ (+1) Increase / → (0) Stable / ↓ (-1) Decrease / ↓↓ (-2) Strong decrease

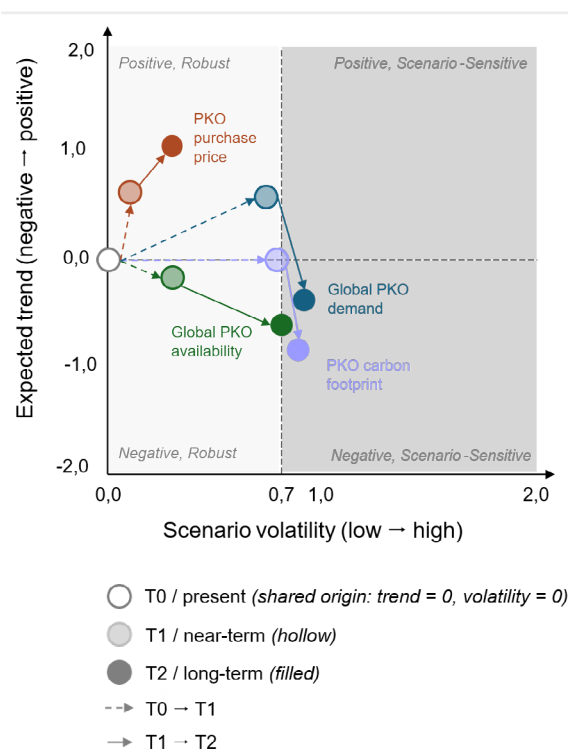


Figure 4. Dynamic robustness map for the palm kernel oil (PKO) case, showing the development of all four Future Performance Indicators (FPIs) from the shared present-day origin (T0) through the near-term horizon (T1) to the long-term horizon (T2), based on the aggregated scenario scores reported in Table 3.

by sufficient productivity or technology gains. For strategic decision-makers, this means that PKO should not be treated as a stable long-term anchor material without active risk management. Instead, it should be considered a feedstock that requires diversification, supplier portfolio adjustment, and close monitoring of regional sourcing risks.

At the same time, the case study demonstrates the value of the proposed framework as a decision-support tool. The layered structure makes it possible to trace a FPI outcome back to underlying drivers and context factors, while the robustness maps provide an intuitive visualization of expected trend and volatility. This combination is particularly useful where strategic raw material choices must integrate technical feasibility, supply security, and sustainability constraints across different organizational levels.

From an application perspective, the PKO results can support sourcing strategy, supplier base redesign,

and the evaluation of production locations for natural fatty alcohols and other PKO-derived value chains. The framework is especially useful where managers need to compare alternatives not only on current cost or availability, but also on their ability to remain viable under multiple future conditions. The case study displays how scenario analysis and robustness maps can be used as an operational tool for resilient feedstock management in the chemical industry.

4. Conclusion

4.1 Strategic Implications for Business Chemistry

The proposed framework provides a structured approach to assessing feedstock robustness that is directly applicable to strategic decision-making in the chemical industry. The PKO case illustrates this concretely: a single robustness map revealed that availability and price move consistently in an unfavorable direction across all three scenarios, while demand shifts from a robust to a scenario-sensitive signal over time. This is a pattern that would be difficult to communicate from qualitative scenario narratives alone, but is immediately visible once translated into a robustness map.

One key implication lies in feedstock portfolio management. Rather than evaluating raw materials in isolation, robustness maps allow companies to compare multiple feedstocks or sourcing strategies based on their robustness profiles, echoing the logic of diversification as a hedge against uncorrelated risk (Markowitz, 1952). In the PKO case, this logic points toward a concrete action: since availability and price are robustly unfavorable rather than merely uncertain, diversification away from PKO is a more defensible strategy than waiting for the uncertainty to resolve.

The framework also provides valuable insights for procurement and supply chain strategy. By linking external developments to internal system drivers and performance indicators, it becomes possible to identify key sources of vulnerability within supply chains, such as supplier concentration, geopolitical exposure, or dependencies on specific production regions. In the PKO case, this surfaced Europe's structural import dependence across all three scenarios. This vulnerability persists regardless of which future materializes, and qualitative scenario narratives alone had not made this

explicit.

A further area of application concerns technology and innovation management. Decisions regarding the adoption of alternative feedstocks, new processing technologies, or bio-based and synthetic substitutes are often characterized by high uncertainty and long investment horizons. The framework supports these decisions by making explicit how different technological pathways affect performance indicators such as cost, availability, and environmental impact under varying future conditions, providing a basis for robust technology roadmapping (Phaal et al., 2004).

In the context of increasing sustainability requirements, the framework also contributes to integrating environmental considerations into strategic decision-making. The PKO case again illustrates this directly: carbon footprint was the one FPI that improved across most scenarios, even as availability and price worsened—a divergence between economic and environmental trajectories that a single, undifferentiated robustness assessment would have obscured.

Finally, the dynamic extension of the robustness map (Section 2.1, Figure 1b) adds a further strategic dimension: because it distinguishes indicators that merely strengthen within a quadrant from those that cross from robust into scenario-sensitive territory, it can draw attention to emerging vulnerabilities, such as PKO demand's shift toward scenario sensitivity, before they become acute, supporting earlier and more anticipatory strategic responses than a static assessment alone would allow.

4.2 Transferability to Other Feedstocks and Industries

Although the framework is illustrated using a specific feedstock case, its conceptual structure is designed to be fully transferable across different raw material systems and industry contexts. The key components—exogenous context drivers, endogenous system drivers, FPIs, and robustness maps—are defined at a level of abstraction that allows adaptation to a wide range of applications.

Transferability is primarily ensured through the modular nature of the framework. While the overall analytical

logic remains constant, individual elements can be adapted to reflect the specific characteristics of different feedstocks. This includes the selection of relevant FPIs, the identification of system-specific endogenous drivers, and the definition of appropriate context drivers and scenarios. As a result, the framework can be applied to bio-based, fossil-based, or synthetic feedstocks, as well as hybrid systems.

Beyond feedstock sourcing, the approach can also be extended to other domains within business chemistry where uncertainty plays a critical role. Examples include technology portfolio decisions, investment planning, or the assessment of regulatory scenarios. In each case, the framework can be used to structure uncertainty, make system responses transparent, and support strategic decision-making through robustness-based diagnostics.

At the same time, effective application requires context-specific adaptation. The relevance of individual drivers, the structure of scenarios, and the interpretation of FPIs depend on the industry setting and decision context. The framework should therefore be understood as a generalizable analytical approach rather than a fixed model.

4.3 Limitations, Future Research, and Conclusion

Despite its advantages, the proposed framework has several limitations that should be acknowledged.

First, the framework relies on expert-based qualitative assessments, particularly in the evaluation of scenario developments and endogenous driver dynamics. While the use of a standardized directional scale enhances consistency, the results remain dependent on expert judgment and may be influenced by cognitive biases or limited information. This introduces a degree of subjectivity that should be considered when interpreting results.

Second, the framework adopts a semi-quantitative representation rather than a fully dynamic or simulation-based modeling approach. While this enhances transparency and usability, it limits the ability to capture complex feedback loops, nonlinear system behavior, or time-dependent interactions in

detail. Dedicated System Dynamics simulations can represent feedback loops, nonlinearities, and time delays more explicitly, as shown in applied quantitative work by Gröne et al. (2019), Glöser et al. (2014) and Glöser-Chahoud et al. (2016); however, developing and calibrating such models is considerably more time- and resource-intensive, and was not feasible within the scope of this study. As a result, the framework is best understood as a diagnostic tool that captures broad directional and relative-magnitude patterns rather than a predictive model capable of precise quantitative forecasting.

Third, the robustness maps are based on relative trends and dispersion, rather than absolute performance levels. While this is consistent with the objective of robustness assessment, it means that the framework does not provide direct guidance on optimal decision choices or precise performance outcomes. Instead, it supports comparative and exploratory analysis.

Fourth, the placement of the robust/scenario-sensitive boundary, set at a volatility of 0.7 in the PKO case (see Section 3, Fig. 4), is itself a judgement call: it was set substantively rather than derived from the data, reflecting the author's judgment that volatility of 1—full disagreement in direction across scenario—would be too high a bar for an indicator to still count as robust. Although the Methods Appendix outlines several calibration approaches, none is free of subjectivity, and a different threshold, or a different substantive criterion, could shift which indicators are classified as robust. This sensitivity should be kept in mind when interpreting the quadrant assignments in Section 3.

Finally, the quality of results depends on the definition of scenarios and system boundaries. If relevant drivers are omitted or scenarios do not sufficiently capture the range of plausible futures, robustness assessments may be incomplete. Careful scenario design and system mapping are therefore critical for meaningful application.

The presented framework offers several avenues for further development, several of which follow directly from the limitations discussed above.

First, the subjectivity inherent in expert-based

directional assessments could be addressed through structured elicitation techniques, such as Delphi-based scoring or inter-rater reliability checks across multiple independent expert panels, to make the degree of assessor agreement transparent and, where possible, reduce subjective bias.

Second, the trade-off between the framework's semi-quantitative approach and the higher precision of full System Dynamics simulations points toward a hybrid research direction: rather than replacing one approach with the other, future work could explore combining the two: using the present framework for rapid, broad-based screening across many feedstocks, and reserving resource-intensive System Dynamics modeling for the small subset of indicators or drivers flagged as most critical or most scenario-sensitive.

Third, the sensitivity of quadrant classification to the placement of the robust/scenario-sensitive boundary, noted above, warrants systematic investigation. Future work could conduct sensitivity analyses across the three calibration approaches detailed in the Methods Appendix, testing how robustly the strategic conclusions of a given case hold up under alternative boundary placements.

Fourth, while the framework was co-developed with practitioners within the applying organization, it has not yet been applied independently at other companies or tested with decision-makers who were not part of the original assessment team. Future research should include applications at additional organizations, as well as structured feedback from downstream users, i.e., procurement or strategy staff who receive a finished robustness map without having been involved in its construction, to assess whether the diagnosis is interpreted and acted upon as intended.

This study develops and demonstrates a scenario-based framework for the assessment of feedstock robustness under conditions of deep uncertainty. By linking exogenous context drivers, endogenous system dynamics, and FPIs within a structured, semi-quantitative analytical logic, the framework makes robustness observable and comparable at the level of concrete decision-relevant indicators—closing the gap between qualitative scenario narratives and quantitative

strategic diagnostics that motivated this study.

Applied to the case of PKO sourcing, the framework surfaces a finding that is not obvious from either qualitative scenario narratives or single-point forecasts alone: PKO emerges as a robust but unfavorable feedstock. Declining availability and rising prices hold consistently across all three scenarios, while only carbon footprint improves; demand, meanwhile, shifts from a robust near-term signal to a scenario-sensitive one further out. This combination of high predictability and unfavorable direction is precisely the kind of insight the framework is designed to reveal, and one that a single-scenario forecast would likely have obscured.

From a business chemistry perspective, the framework offers a practical diagnostics tool that supports the comparison of sourcing options and the identification of system vulnerabilities without requiring specialist modeling expertise. While demonstrated through the PKO case, its modular structure is designed to be transferable to other bio-based, fossil-based, and hybrid feedstocks, as well as to broader strategic questions beyond sourcing.

These contributions should be read alongside the framework's limitations: its reliance on expert judgment, its semi-quantitative rather than fully dynamic treatment of system behavior, the sensitivity of its robust/scenario-sensitive boundary to calibration choices, and the fact that it has so far been applied and evaluated only within the originating organization. Future research, including structured expert-elicitation methods, sensitivity analysis of the robustness boundary, hybrid approaches combining the framework with dedicated System Dynamics modeling, and application by external organizations and downstream users, can address these limitations directly.

In summary, the framework provides a structured and interpretable way to assess feedstock robustness under deep uncertainty, offering both a generalizable diagnostic tool and, in the PKO case, a concrete example of the kind of counter-intuitive strategic insight it is designed to surface.

Statement of AI Usage

During the preparation of this work the authors

used generative AI to support language editing, improve readability, and review the manuscript for inconsistencies. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final manuscript. All scientific content, analyses, interpretations, and conclusions were developed and reviewed by the authors.

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6. Methods Appendix

This appendix provides the methodological detail summarized in Section 2: the selection criteria for Future Performance Indicators (FPIs), the role of endogenous and exogenous drivers, the available approaches for calibrating the robustness/scenario-sensitivity boundary, and a full worked example of how robustness-map coordinates are derived.

FPI selection criteria.

FPIs are defined *ex ante* based on their strategic relevance. Relevance is assessed against three criteria: materiality for the sourcing decision at hand (i.e., whether the indicator meaningfully influences procurement, investment, or technology choices), availability of sufficiently reliable directional assessments across scenarios, and interpretability for non-technical stakeholders, so that the resulting robustness map remains accessible to cross-functional audiences rather than requiring specialist modeling expertise. In the context of chemical feedstock sourcing, typical FPIs include demand, availability, price, and environmental performance (e.g., carbon footprint). FPIs are typically interdependent rather than reducible

to a single metric—for example, PKO Purchase Price's drivers include Global PKO Availability and Global PKO Demand (see Figure 3)—so that trade-offs between cost, availability, and sustainability remain explicit rather than being aggregated away.

Endogenous and exogenous drivers.

Endogenous feedstock drivers represent the internal structure of a feedstock system and act as the transmission layer between external context and FPI outcomes. They can be grouped into recurring categories—sourcing structures, technological performance, cost structures, supply chain stability, and environmental characteristics—operationalized differently depending on the feedstock (e.g., through production costs, yield levels, supply resilience, land use, or emissions). Drivers are neither fully controllable nor entirely exogenous: some can be influenced through strategic decisions such as diversification or technological investment, while others are largely constrained by system characteristics. Drivers are also interdependent, with individual drivers often affecting multiple FPIs simultaneously; rather than explicitly modeling all interactions, the framework captures these relationships through transparent, expert-informed linkages that preserve interpretability.

Exogenous context drivers define the boundary conditions under which these internal dynamics unfold. They are typically identified using a STEEP scan, societal, technological, ecological, economic, and political dimensions (Morrison and Wilson, 1996; Markley, 2011), and, in feedstock sourcing, include regulatory developments, global demand trends, climate-related impacts, geopolitical dynamics, and technological change. Scenario development does not necessarily require the creation of new scenario sets: the framework is compatible with existing, sector-specific foresight studies (e.g., explorative industry foresight scenarios on the future of specialty chemicals, or national-level scenario studies on the chemical, pharmaceutical, and biotechnology sectors), which can be adopted as structured inputs to enhance both the credibility and efficiency of the analysis. For each scenario, exogenous context drivers are assessed for their directional development over the relevant time horizons, grounding scenario narratives in a traceable,

semi-quantitative structure rather than leaving them as free-standing qualitative stories. They do not determine outcomes directly but provide the structured inputs that are propagated through endogenous feedstock drivers and ultimately reflected in the development of FPIs.

Boundary calibration approaches.

The plane of a robustness map is divided into four regions—positive/robust, positive/scenario-sensitive, negative/robust, negative/scenario-sensitive—by a boundary along the volatility axis. In the stylized illustration in Figure 1, this boundary is set as an equal partition of the axis, so that low- and high-dispersion regions receive equal visual weight; this keeps the illustration neutral but does not reflect the empirical distribution of any specific case. In an applied setting, the boundary should instead be calibrated to the case at hand. Possible calibration approaches include: (i) a symmetric split, as exemplified in Figure 1, which is the most transparent default but arbitrary with respect to the actual data; (ii) a data-driven threshold, for example placed at the median or mean dispersion observed across all assessed FPIs or drivers, so that the boundary reflects the empirical spread of the specific case; or (iii) a substantively defined threshold, tied to a concrete interpretive criterion—for instance, that volatility below the threshold corresponds to less than one coding step of directional disagreement across scenarios (this is the approach used for the PKO case, see Section 3.4). Regardless of approach, the placement of the boundary should be reported explicitly, as it directly determines which indicators are classified as robust (see the Limitations in Section 4.3).

Deriving robustness-map coordinates.

Robustness-map coordinates are derived bottom-up in three steps.

Step 1: Directional scoring. For each scenario and time horizon, every exogenous context driver and endogenous feedstock driver is assessed on a standardized five-point directional scale: strong decrease (−2), decrease (−1), stable (0), increase (+1), strong increase (+2). Where a context driver relates inversely to the endogenous feedstock driver it feeds into (e.g., stronger land-use regulation reduces rather than increases available

plantation area), its score is sign-adjusted before aggregation.

Step 2: Weighted aggregation to the FPI trend (vertical axis). Each endogenous feedstock driver is assigned a weight, based on expert judgment, reflecting its relative importance for the FPI it feeds into. An FPI's trend value for a given scenario and time horizon is the weighted sum of its drivers' directional scores.

Worked example: Global PKO Availability (Section 3). Global PKO availability is decomposed into four endogenous drivers: total plantation area (weight 35%), fresh fruit bunch (FFB) yield per hectare (30%), PKO extraction potential (25%), and domestic supply chain stability (10%) (Table 2). For the Sustainability Paradigm scenario, 2035–2050: total plantation area is stable (0), FFB yield shows strong increase (+2), PKO extraction potential is stable (0), and domestic supply chain stability shows increase (+1). The weighted trend value is:

$$(0.35 \times 0) + (0.30 \times (+2)) + (0.25 \times 0) + (0.10 \times (+1)) = 0 + 0.60 + 0 + 0.10 = +0.70$$

which matches the value reported in Table 2. The same calculation applied to the 2025–2035 period, and summed across both periods, yields each scenario's long-term (2025–2050) trend value: +0.5 for Sustainability Paradigm, −0.5 for Deceptive Calm, and −1.5 for Turbulent Times. Averaging across the three scenarios gives the vertical-axis (trend) position plotted in Figure 4: −0.5, reflecting a scenario-independent gradual decline in availability over the long term.

Step 3: Deriving dispersion (horizontal axis). The horizontal-axis value for an FPI at a given time horizon is the population standard deviation (SD) of its three scenario-specific weighted trend values from Step 2—that is, how differently the scenarios develop, rather than how strongly or in which direction the FPI moves. SD is calculated as $\sqrt{(\sum (x_i - \bar{x})^2) / n}$ where x_i is each scenario's weighted trend value from Step 2, $\bar{x}$ is the mean of those three values, and n is the number of scenarios ($n=3$). For Global PKO Availability, 2035–2050, the three scenario values from Table 2 are +0.7 (Sustainability Paradigm), −0.8 (Deceptive Calm), and −1.1 (Turbulent Times):

$$\bar{x} = (+0.7 + (-0.8) + (-1.1)) / 3 = -0.4$$

$$SD(+0.7, -0.8, -1.1) = \sqrt{((0.7 - (-0.4))^2 + ((-0.8) - (-0.4))^2 + ((-1.1) - (-0.4))^2) / 3} \approx 0.79$$

This is the value plotted on the horizontal axis in Figure 4. Because dispersion reflects divergence between scenarios rather than the direction or magnitude of change, two FPIs can share the same negative trend yet fall into different quadrants—one robust, one scenario-sensitive—depending on how consistently the scenarios agree on that direction. Global PKO Availability is used here only to illustrate the calculation; the same two-step procedure (Steps 2–3) is applied identically to each of the other three FPIs (Global PKO Demand, PKO Purchase Price, PKO Carbon Footprint). The resulting trend and dispersion values for all four FPIs are summarized in Table 3 and plotted together in Figure 4.

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