POLYMER FRONTIERS:

A Comprehensive Data-Driven Analysis of Emerging Trends

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Synopsis

The PetroChina (Shanghai) Advanced Materials Research Institute (SAMRI), a key research arm under PetroChina Company Limited, plays a central role in advancing materials science and engineering to support China's energy and chemical industries. SAMRI's mission is to drive PetroChina's strategic transformation from a traditional refinery and petrochemical supplier to an innovative advanced and sustainable materials provider. SAMRI engaged top scientists worldwide to jointly build state-of-the-art innovation platforms that span fundamental research, product and application development with specialized technical support, demonstration pilot plants, and full scale commercial implementation capabilities. Focusing on key technical bottlenecks across the entire value chain, SAMRI strives to evolve into a world-class innovation hub for advanced, sustainable and intelligent materials.

CAS, a division of the American Chemical Society, is a global leader in scientific knowledge management and data analytics. CAS curates the world's most comprehensive collection of chemistry-related scientific information, the CAS Content Collection™, spanning over 150 years of journal articles, patents, and curated scientific data. Beyond content aggregation, CAS applies advanced data analytics, domain expertise, and visualization technologies to transform complex scientific information into actionable insights. These capabilities position CAS uniquely to identify emerging research trends, map innovation networks, and assess technological trajectories across the global scientific landscape.

This report, as a collaborative effort between PetroChina (Shanghai) Advanced Materials Research Institute and CAS, reflects a shared recognition that the future of polymer innovation depends on integrating deep industrial expertise with global-scale scientific intelligence. By combining PetroChina's application-driven materials research perspective with CAS unparalleled data coverage and advanced analytics capabilities, this report delivers a comprehensive, evidence-based view of polymer research and development. Through systematic mapping of research hotspots, evolving polymer architectures, and emerging application domains, the analysis supports informed decision-making, fosters cross-disciplinary exchange, and accelerates the translation of polymer science into industrial and societal impact for the global polymer research community.

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1. Introduction: The Evolving Global Polymer Innovation Landscape

Polymers are among the most consequential material platforms in modern industrial history. Over the last century, they have reshaped manufacturing, healthcare, energy systems, electronics, and consumer products at global scale. From Baekeland's 1907 synthesis of Bakelite, the first fully synthetic plastic with a combination of properties not found in natural materials, to today's programmable, self-healing, stimuli-responsive, and biodegradable systems, polymer science has progressed from empirical materials discovery to increasingly precise molecular and process design.[1] The global polymer industry, which approached $500 billion in annual sales nearly a decade ago, has continued expanding as polymers enable applications from life-saving medical devices to clean energy technologies.[2]

This success, however, has also made the field more complex. Polymer innovation now sits at the intersection of synthetic chemistry, physics, biology, engineering, computation, and artificial intelligence. The accessible design space is effectively vast: even a simple 50-unit AB copolymer presents on the order of 10^{15} possible sequences.[3] At the same time, traditional materials development timelines—often 15–25 years from discovery to scaled adoption—are increasingly misaligned with the pace of technological change, regulatory evolution, and sustainability demands.[4] In this environment, competitive advantage depends not only on scientific excellence, but on the ability to understand how research trajectories, market pull, regional capabilities, and enabling technologies are evolving together.

From Empirical Discovery to Data-Driven Design

The history of polymer science is not only a record of materials breakthroughs; it is also a sequence of shifts in how innovation occurs. That evolution provides essential context for interpreting the current landscape.

The Foundational Era (1907-1945) began with materials solving immediate practical problems while revealing scientific puzzles. Bakelite's success stemmed from its unique combination of electrical insulation, heat resistance, and moldability.[1] Wallace Carothers' nylon development at DuPont demonstrated that synthetic polymers could replace expensive natural materials with superior performance.[5] These breakthroughs emerged through systematic experimentation rather than theoretical understanding: the macromolecular hypothesis itself remained controversial until Hermann Staudinger's work in the 1920s-1930s established that polymers consisted of thousands of repeating units connected by covalent bonds.[6] World War II accelerated development, with polyethylene, synthetic rubber, and silicones emerging from military needs, establishing petrochemical companies as polymer innovators.

Rationalization and Specialization (1945-2015) transformed the field from empirical discovery to rational design. Theoretical advances, particularly Ziegler-Natta catalysis, enabled property prediction and control.[7] Experimental capabilities expanded dramatically: size exclusion chromatography democratized molecular weight characterization; techniques like small-angle neutron scattering, atomic force microscopy, and matrix-assisted laser desorption/ionization mass spectrometry transitioned from specialized facilities to routine capabilities.[8] The polymer portfolio diversified from commodities toward specialty materials: engineering plastics offering metal-like performance, conducting polymers enabling organic electronics, and biomedical polymers for drug delivery. Controlled radical polymerization techniques, including atom transfer radical polymerization (ATRP), reversible addition-fragmentation chain transfer (RAFT), and ring-opening metathesis polymerization (ROMP), revolutionized synthesis by providing architectural control with vastly expanded monomer compatibility.[8]

However, this progress introduced fragmentation. Polymer science became

increasingly specialized, with distinct subfields advancing at different rates and with different technical languages. Industrial organizations were challenged to integrate expertise across synthesis, characterization, processing, formulation, and end-use performance—an increasingly difficult task even for large enterprises. At the same time, academic and industrial innovation systems diverged in incentives and timelines, widening the translational gap. Meanwhile, the geographic center of innovation began to shift, especially toward Asia.

The Current Inflection Point: Why Comprehensive Analysis is Essential

Today's polymer landscape differs from prior eras not simply in scale, but in structure. Innovation is being reshaped simultaneously by sustainability constraints, regional realignment, application convergence, and digital/biological technologies. These forces are interconnected, and understanding their interaction is now essential for strategic decision-making.

1. The Sustainability Imperative Reshaping Design Priorities. Environmental considerations evolved from peripheral constraints to central requirements driving major research investments and regulatory frameworks globally.[9] Achieving sustainability while matching established materials' performance at viable cost presents immense complexity: biodegradable polymers must function reliably during use while degrading predictably afterward and bio-based feedstocks must scale to commodity volumes while competing economically with petrochemicals. This transformation extends beyond material substitution to a fundamental rethinking of polymer lifecycles from synthesis through end-of-life. Systematic tracking reveals which approaches are gaining momentum versus remaining exploratory, where technical barriers persist versus showing resolution, and which organizations lead different aspects of the transition. The convergence of regulatory pressure, technological maturation, and demonstrated commercial viability positions sustainable polymers as a defining competitive arena for the coming decade.

2. Polymer Innovation Capacity Redistributed Geographically. The global center of polymer innovation has shifted dramatically toward Asia-Pacific, altering competitive dynamics, supply chain structures, and technology access pathways. This transformation represents a quantitative shift in publication and patent volumes and reflects the emergence of integrated innovation ecosystems combining fundamental research capability, manufacturing infrastructure, and substantial market demand within the same geographic regions. Regional nuances reveal distinct innovation strategies: some emphasize comprehensive research coverage across polymer types, others focus on efficient translation from research to high-value commercial applications, while others concentrate on specific application domains. Strategic decisions regarding partnerships, competitive intelligence, and market positioning require understanding where specific capabilities reside, how regional priorities align with organizational needs, and which institutions lead technological areas. This geographic restructuring of innovation capacity has profound implications for global competitiveness and technology leadership.

3. Application-Driven Innovation Dissolving Traditional Boundaries. Historical separations between polymer application domains are dissolving as advanced technologies demand materials that address multiple requirements. Battery systems require polymers that provide ionic conductivity, mechanical stability, and thermal safety. Flexible electronics need mechanical compliance, electrical functionality, and environmental protection. Sustainable packaging must match petroleum-based performance while ensuring appropriate end-of-life fate. Success depends more on multifunctional integration rather than optimization of single properties. Systematic analysis comparing journal and patent landscapes illuminates how innovations translate from laboratory concepts to commercial products, revealing where breakthrough materials show strong academic interest but limited commercial development, where rapid patent activity indicates

technologies approaching market deployment, and where established materials are being adapted for new application domains through processing or formulation innovations.

4. Technology Convergence Creating New Paradigms. Polymer innovation increasingly intersects with transformative technologies from adjacent fields. Synthetic biology enables monomer production from renewable feedstocks, offering pathways to sustainable polymer production at an industrial scale.[3, 9] Additive manufacturing creates possibilities for complex geometries and functional gradients impossible through conventional processing, fundamentally changing how polymers are designed and deployed.[4] Computational approaches accelerate materials discovery by exploring vast chemical spaces more efficiently than traditional experimental methods. These converging technologies create opportunities for organizations that can integrate capabilities across traditional disciplinary boundaries, while presenting challenges for those with expertise concentrated in single domains. Understanding where these technologies create opportunities versus face implementation barriers enables strategic investment in the most promising directions.

The Value of Comprehensive Landscape Analysis

Taken together, these transformations have created a polymer innovation environment that is too dynamic and interconnected to navigate through intuition alone. Expert judgment remains indispensable, but it is increasingly most powerful when paired with quantitative evidence on research momentum, institutional leadership, patenting behavior, and technology maturation.

This report addresses that need through a systematic analysis of nearly one million polymer-related journal and patent records from 2015–2025. Using a combination of bibliometric methods, natural language processing, and cross-domain comparison, we examine the global polymer landscape across five dimensions: **Global innovation mapping** – identifying where polymer research and patent activity are concentrated geographically, and which organizations lead by country and institution type. **Trend detection and topic momentum** – distinguishing fast-rising topics from stable or declining areas using large-scale text analytics. **Application-focused analyses**– analyzing materials, key players, and publication/patent patterns in energy storage, sustainable polymers, flexible electronics, and membrane technologies (**Figure 1**). **Research-to-commercialization translation** – comparing journal and patent landscapes to evaluate which technologies are moving toward market adoption and where translational gaps persist. **Frontier scouting** – identifying emerging polymer classes, methods, and capability clusters that show early but meaningful momentum.

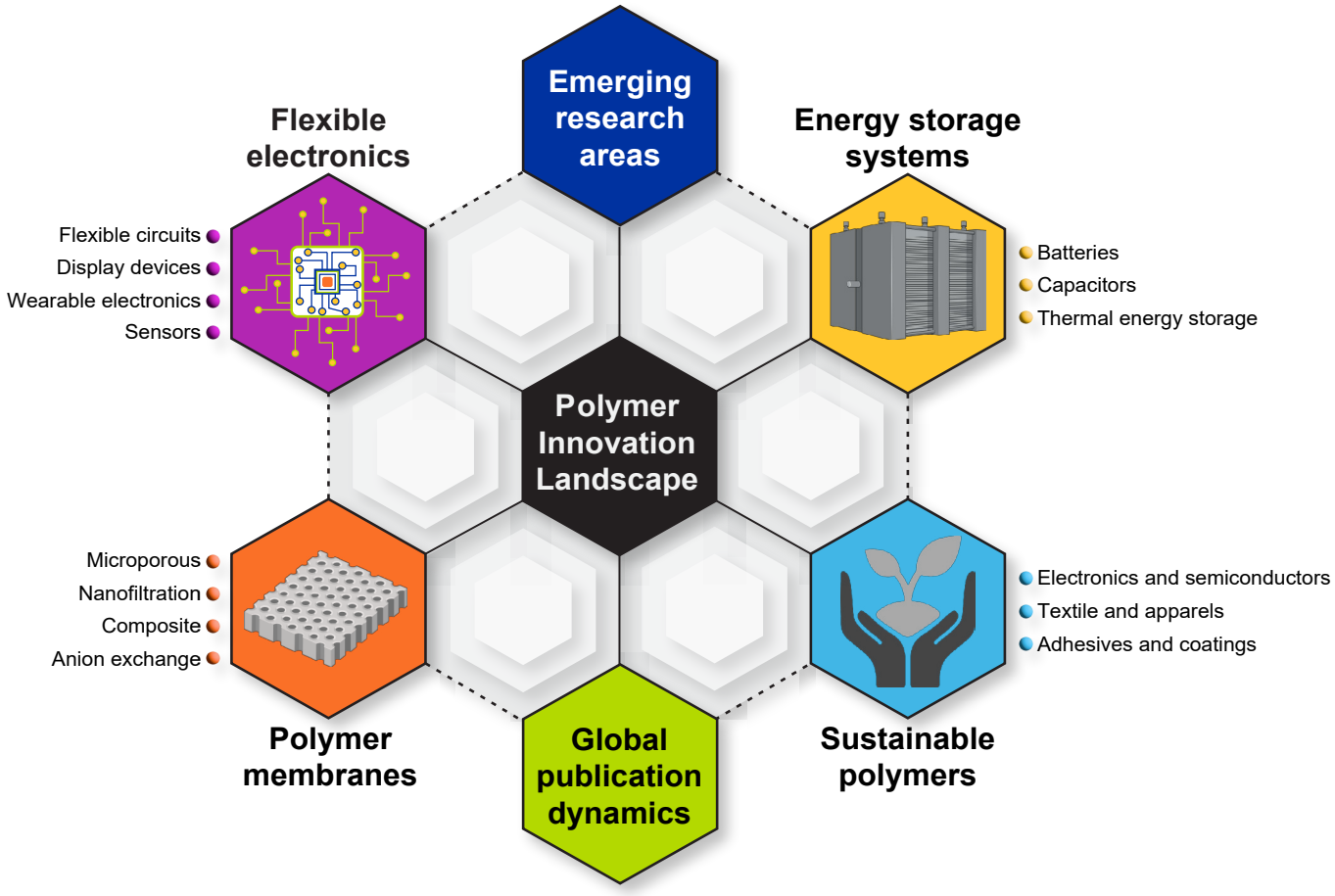


Figure 1. Schematic overview of the polymer innovation landscape presented in this report. Figure partially created using icons from www.BioRender.com

The goal is not only to describe the polymer landscape, but to make it actionable. The industry is undergoing structural change: petroleum-based production systems are being challenged by bio-based and circular alternatives; legacy polymer classes are being re-evaluated against sustainability and regulatory criteria; and application demands increasingly favor multifunctional, system-level material solutions. In this context, decisions on R&D investment, partnerships, talent development, and market entry must be informed by a clear view of where innovation is occurring, who is driving it, and how scientific advances are translating into commercial opportunity.

By integrating research and patent evidence across geographies and applications, this report provides a data-grounded perspective on the evolving polymer innovation landscape—one intended to support both scientific prioritization and industrial strategy.

2. Data, Methods, and Analytical Framework

2.1 Scope and Coverage of CAS Polymer Knowledge Base

Using CAS proprietary chemical structure and scientific terms indexing systems, subject matter experts at CAS crafted a comprehensive structure-based search strategy to accurately retrieve publications related to polymers.

The search strategy, replying on identification of substances classified as polymers in the CAS REGISTRY®, resulted in ~2.5 million substances spread across ~5.8 million publications in the CAS Content Collection. The search strategy (**Figure 2**) was further refined by applying two criteria:

- Substances containing at least one carbon atom and appearing in more than two references (approximately 235,000 polymer substances cited in 5.3 million documents).
- Restricting CAS Sections to those specific to polymers, namely sections 35–40, 43, 44, and 51 (**Table 1**).

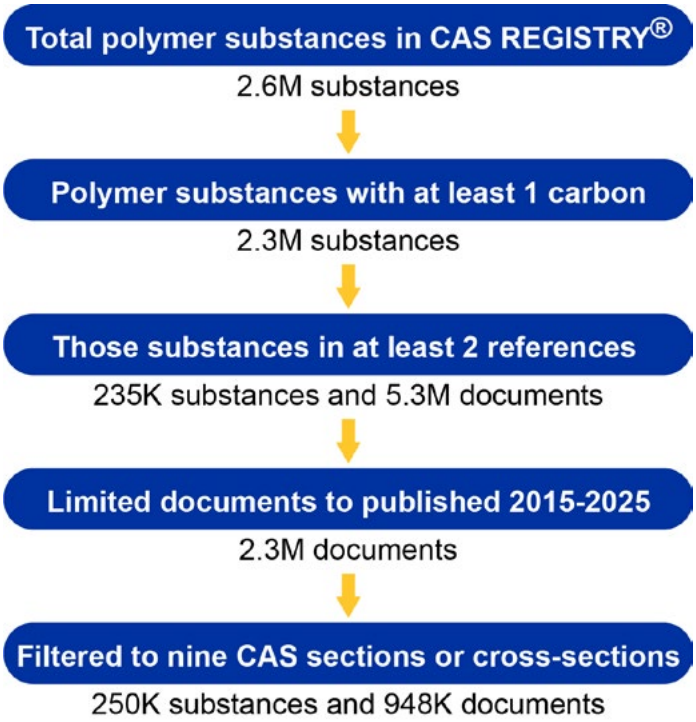


Figure 2. Polymer related document search strategy and data scope.

Table 1. The list of CAS Sections that are included in this study and their associated document numbers.

CAS Section Number and Name	Number of Docs
38. Plastics Fabrication and Uses	276K
37. Plastics Manufacture and Processing	220K
35. Chemistry of Synthetic High Polymers	99K
40. Textiles and Fibers	74K
39. Synthetic Elastomers and Natural Rubber	64K
51. Fossil Fuels, Derivatives, and Related Products	40K
43. Cellulose, Lignin, Paper, and Other Wood Products	29K
36. Physical Properties of Synthetic High Polymers	27K
44. Industrial Carbohydrates	8K

Additionally, the search was limited to documents published between 2015 and 2025. This methodology, reliant on CAS chemical structure-based indexing capabilities encompassed in the CAS REGISTRY, and robust indexing as part of the CAS Content Collection resulted in a dataset comprised of ~948K publications, 250,000 unique polymeric substances, ~50,000 unique CAS concepts (>10 million CAS concept mentions), all of which were utilized in the data analysis. Data covers the period 2015-2025 with data only for the months January to November in 2025.

2.2 Advanced Analytics and NLP Methodologies for Trend Discovery

Our comprehensive analysis of the polymer landscape employs a multi-dimensional methodological framework combining bibliometric analysis, patent intelligence, and advanced natural language processing (NLP) to map the polymer landscape.

A list of data fields from each of the above ~948K publications were extracted from the CAS Content Collection, including:

- Bibliographic data from scientific literature (titles, abstracts, publication years, authors, research institutions, countries/regions, citations, etc.)
- Patent documents from 110 global patent authorities (patent offices, patent assignees, countries/regions, patent families, titles, abstracts, claims, publication years, etc.)
- Indexed CAS scientific concepts, applications, and roles associated with publications.
- Indexed CAS chemical substance (CAS Registry Numbers®, chemical structures, role functions, etc.)

Patent Intelligence and Competitive Landscape: Identified leading patent assignees based on patent family volume distinguished between commercial and noncommercial entities to understand innovation strategies and technology transfer patterns.

Research and Publishing Trends: Pinpointed leading research institutions using a combination of publication volume and citation impact, revealing quantity and quality-focused research strategies across global institutions.

Geographical Insights: Mapped global research activity by analyzing the country/region and organizational affiliations, revealing shifts in regional dominance and the emergence of new innovation centers.

Keyword and Concept Mining: Comprehensive searches across titles, abstracts, and CAS indexed scientific concepts and substances while incorporating synonyms and abbreviations to ensure complete coverage of the research landscape.

NLP Analysis: Identified more than 200 and 1,000 emerging topics in the field in the context of journal and patent publications, respectively, using advanced NLP techniques. Our methodology involved extracting candidate phrases (1 to 6 words in length) from the abstracts and titles (and claims for patent publications). The identified candidate phrases underwent initial AI-based classification followed by multiple rounds of expert validation to refine categorization. The resulting categorized emerging topics are presented in several CAS TrendScape maps, designed to visually convey scientific interest and growth patterns for a vast number of topics. For detailed methodologies of our NLP analysis please see Iyer et al.[10] and Hughes et al.[11]

3. Data-Driven Identification of Global Polymer Research Themes

3.1 Global Publication Dynamics and Competitive Research Positioning

The global polymer research landscape from 2015 to 2025 reveals a field characterized by substantial commercial interest and geographically concentrated innovation patterns. Analysis of nearly one million publications from the CAS Content Collection™ provides unique insights into how polymer science has evolved over the past decade, highlighting the interplay between academic research and industrial development.

3.1.1. Global Publication Trends of Polymer Research

The polymer field demonstrates a striking dominance of patent activity over academic publishing, with patent families comprising 72% of all polymer-related publications compared to 28% for journal articles (**Figure 3**). This 2.5:1 ratio of patents to journal publications significantly exceeds typical ratios observed in many scientific disciplines, underscoring the commercial value and industrial relevance of polymer innovations. The distribution suggests a mature field where technological applications and intellectual property protection take precedence over fundamental discovery.

Temporal analysis reveals distinct patterns between journal and patent publications over the decade. Journal article output has remained remarkably stable, hovering around 24,000-26,000 publications annually with minimal year-to-year variation. This consistency suggests a mature academic field with established research communities and predictable funding streams. In contrast, patent family filings show greater volatility, with notable peaks in 2017-2019 when annual filings reached approximately 67,000 families. The subsequent decline in patent activity from 2020 onwards, dropping to around 58,000 families by 2021, likely reflects multiple factors including pandemic-related disruptions to industrial R&D activities and potential market saturation in certain polymer application areas.

The preliminary data for 2025 showing reduced publication counts should be interpreted cautiously, as these numbers reflect incomplete year data at the time of analysis. However, the

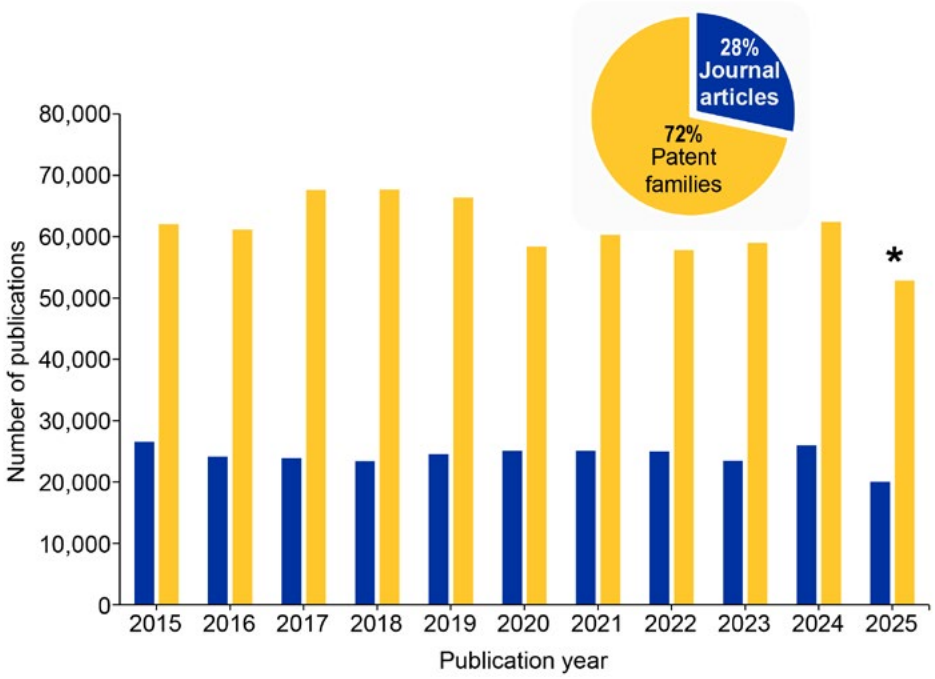


Figure 3. Annual distribution of polymer-related journal articles and patent families from 2015-2025, with inset pie chart showing overall distribution of patent families and journal articles from the CAS Content Collection. *Data only for the months January to November in 2025.

overall trend suggests a field transitioning from rapid expansion to consolidation, where quality and application-specific innovations may be prioritized over volume.

3.1.2.Geographic Distribution of Polymer Innovation

The geographic analysis reveals an unprecedented concentration of polymer research and development in Asia, particularly China, that has fundamentally reshaped the global innovation landscape (**Figure 4**). China's dominance is extraordinary, contributing over 105,000 journal articles and more than 365,000 patent families during the study period. This represents approximately 40% of global journal output and an overwhelming 56% of all patent families. The scale of China's engagement in polymer science exceeds the combined output of the next four countries, establishing it as the undisputed global leader in polymer innovation by volume.

Japan emerges as the second major contributor with approximately 15,000 journal articles and 125,000 patent families, demonstrating a particularly strong emphasis on commercial development with an 8:1 patent-to-publication ratio. This pattern reflects Japan's industrial strength in materials science and its strategic focus on protecting intellectual property in high-value polymer applications. South Korea follows a similar trajectory with roughly 10,000 journal articles but 45,000 patent families, indicating a commercialization-focused research ecosystem.

The United States presents a more balanced profile with approximately 22,000 journal articles and 35,000 patent families, suggesting a different innovation model that emphasizes fundamental research alongside commercial development. This 1.6:1 patent-to-journal ratio is notably lower than Asian counterparts, potentially reflecting differences in patenting strategies, academic funding structures, or industrial R&D priorities.

European contributions show interesting variations, with Germany producing approximately 10,000 journal articles and 20,000 patent families, while France demonstrates higher patent intensity relative to its journal output. The inset data reveals smaller but significant contributors, with India showing

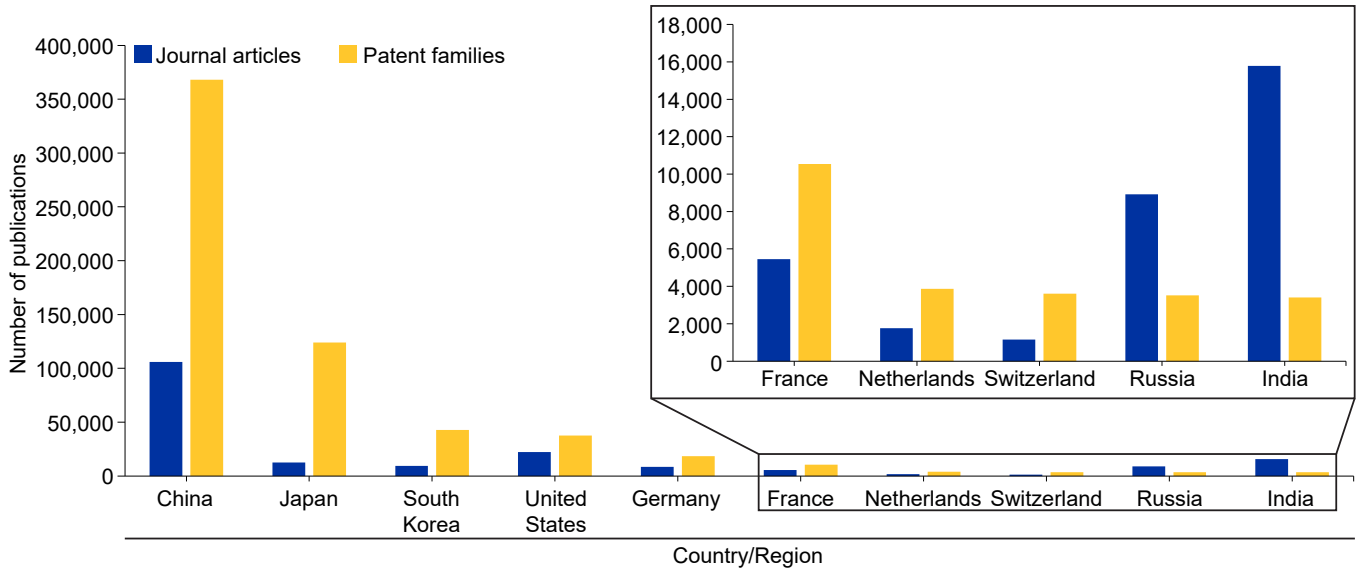


Figure 4. Geographic distribution of polymer-related journal articles and patent families by country/region (2015-2025), with the inset bar graph showing zoomed in version for France, Netherlands, Switzerland, Russia, and India. Data includes journal articles and patent families in the field of polymers for the period 2015-2025 from the CAS Content Collection.

emerging strength with 16,000 journal articles, comparable to established research nations, though with proportionally fewer patents, suggesting a research ecosystem still building commercial translation capabilities.

3.1.3. Institutional Excellence and Research Impact

The institutional landscape of polymer research reveals a complex ecosystem where research quality, as measured by citation impact, does not always correlate with publication volume (**Figure 5**). The analysis of leading research organizations demonstrates that institutions from diverse geographic regions can achieve high scientific impact despite varying publication strategies.

National University of Singapore emerges as the citation leader with an average of approximately 52 citations per publication, despite producing fewer than 500 articles. This exceptional impact suggests highly selective publication strategies focusing on breakthrough research. Similarly, several Western institutions including Northwestern University, Massachusetts Institute of Technology, and Imperial College London achieve citation rates exceeding 45 per publication, indicating research that significantly influences the field.

Chinese institutions dominate in terms of absolute publication volume, with the Chinese Academy of Sciences producing over 6,000 articles, followed by University of science and technology of China and Tsinghua University with approximately 1,000 articles each. However, their citation impact varies considerably, with the Chinese Academy of Sciences achieving around 30 citations per publication while some other high-volume Chinese institutions show lower average impact. This pattern suggests different institutional strategies, with some prioritizing comprehensive coverage of polymer research while others focus on specific high-impact areas.

The presence of institutions from diverse countries—Belgium (Ghent University), Saudi Arabia (multiple institutions), and various

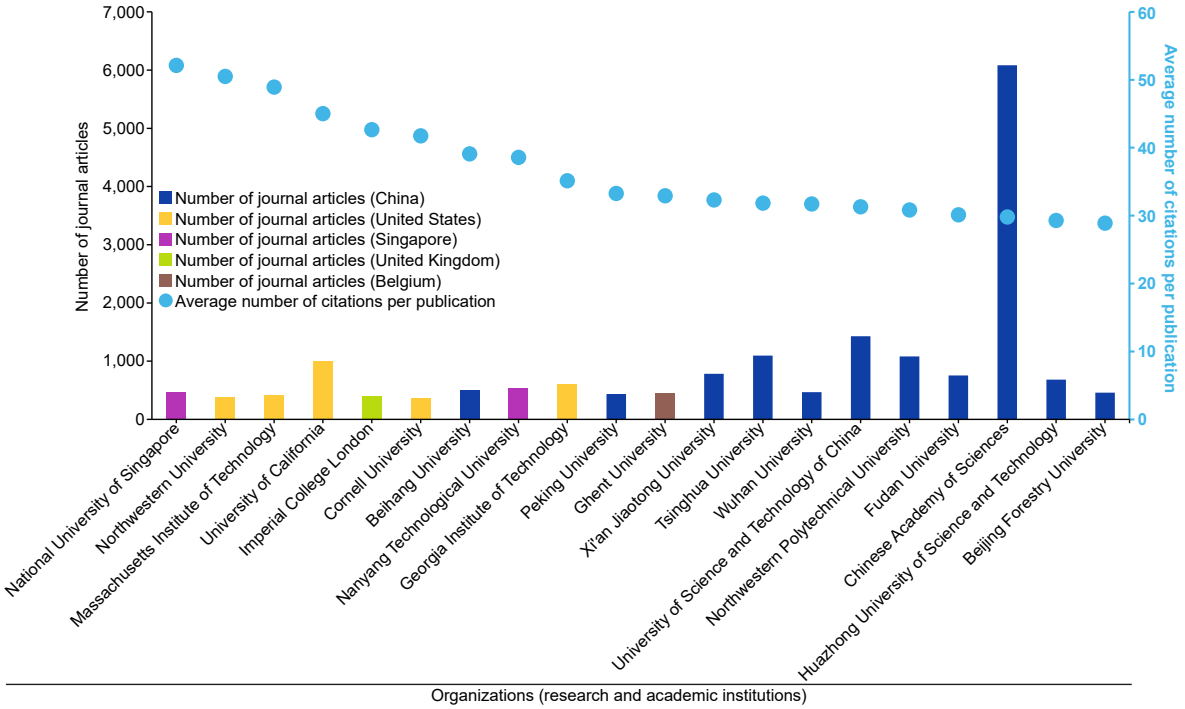


Figure 5. Research output (publication volume) and impact (average citation count per publication) for leading organizations (research and academic institutions) in the field of polymers. Data includes journal articles for the period 2015-2025 from the CAS Content Collection.

Asian and Western universities—among the top publishers indicates the global nature of polymer research. The data reveals that research excellence in polymers is not confined to traditional scientific powerhouses but is increasingly distributed across emerging research centers worldwide.

3.1.4.Commercial Innovation Landscape in Polymer Technologies

The commercial patent landscape provides crucial insights into how different industries are driving polymer innovation (**Figure 6**). Chinese state-owned enterprises dominate patent filings, with Sinopec leading at over 10,000 patent families, followed by China National Petroleum Corporation (CNPC) with approximately 4,000 families. This massive patent portfolio from oil and gas companies reflects China's strategic approach to transitioning from basic petrochemical production to high-value polymer materials, leveraging their feedstock advantages and vertical integration capabilities.

The chemical industry sector shows more geographic diversity in patent leadership. LG Chem from South Korea leads with approximately 6,500 patent families, followed by Japanese companies including Toray Industries, Mitsubishi Chemical, and Sumitomo Chemical, each with 4,000-6,000 families. These companies represent traditional chemical industry powerhouses that have systematically built comprehensive patent portfolios across diverse polymer applications. The strong showing of Japanese chemical companies, despite Japan's smaller overall publication numbers, indicates highly efficient commercial R&D operations with clear intellectual property strategies.

Notable is the presence of companies from different sectors: Fujifilm Holdings and Toppan Holdings representing printing and imaging industries, and Bridgestone and Michelin from tire and rubber manufacturing. Their significant patent portfolios (2,000-3,500 families each) demonstrate how polymer innovation extends

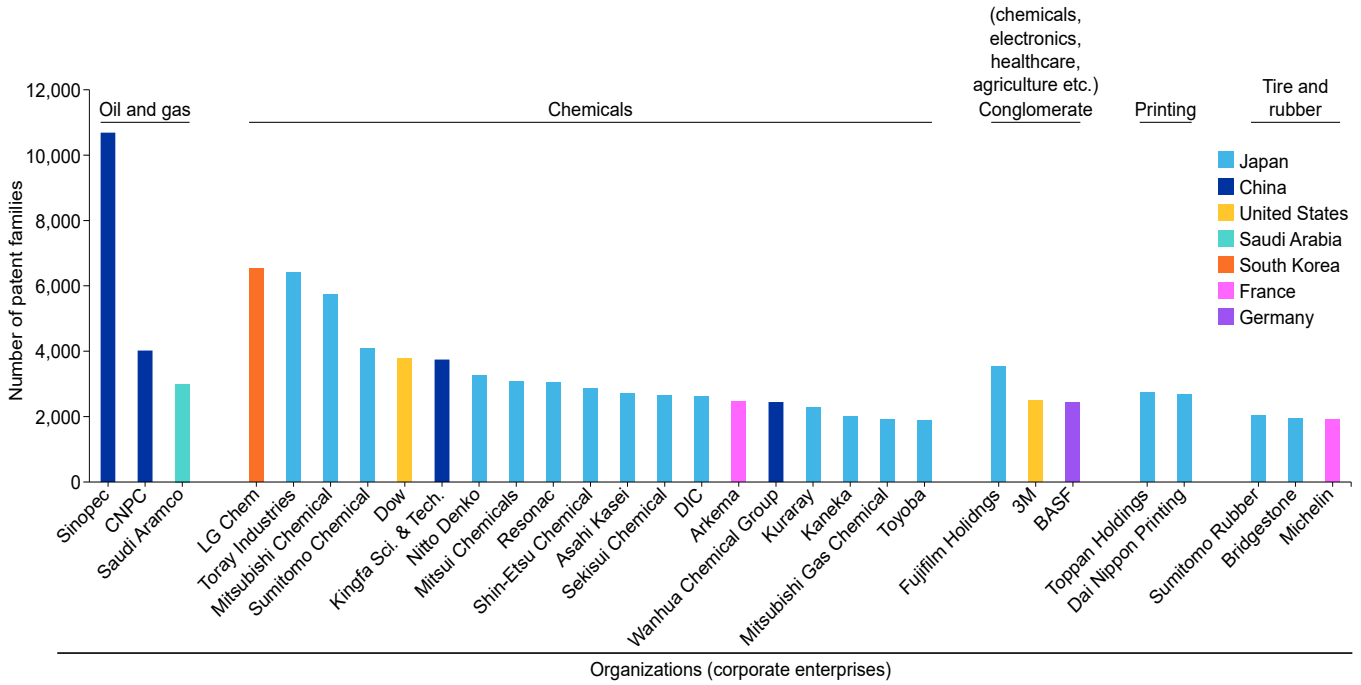


Figure 6. Leading organizations (corporate enterprises) in polymer research by number of patent families, organized by industry sector and country of origin. Data includes patent families in the field of polymers for the period 2015-2025 from the CAS Content Collection.

beyond traditional chemical companies to end-use manufacturers who develop specialized materials for their specific applications.

The geographic distribution of leading commercial patent assignees reveals distinct national innovation strategies. Japanese companies show remarkable efficiency in converting R&D investments into patents, with multiple companies appearing in the top tier despite Japan's smaller overall research base. Korean companies, particularly in electronics and chemicals, demonstrate focused innovation in high-value applications. The limited presence of Western companies in the top patent filers—primarily BASF from Germany and scattered U.S. companies—suggests different approaches to intellectual property protection or potentially indicates a shift in global polymer innovation centers.

3.1.5. Academic Patent Activity and Technology Transfer Potentials

The non-commercial patent landscape, dominated by academic and research institutions, provides insights into university-industry collaboration and technology transfer patterns (**Figure 7**). The Chinese Academy of Sciences stands as an outlier with nearly 8,000 patent families, exceeding the combined output of the next ten academic institutions. This extraordinary patent activity from a research institution reflects China's unique innovation model where academic institutions are strongly incentivized to pursue commercializable research and actively engage in technology transfer.

Chinese universities dominate the non-commercial patent landscape, representing 81% of all academic patent families. Institutions such as South China University of Technology,

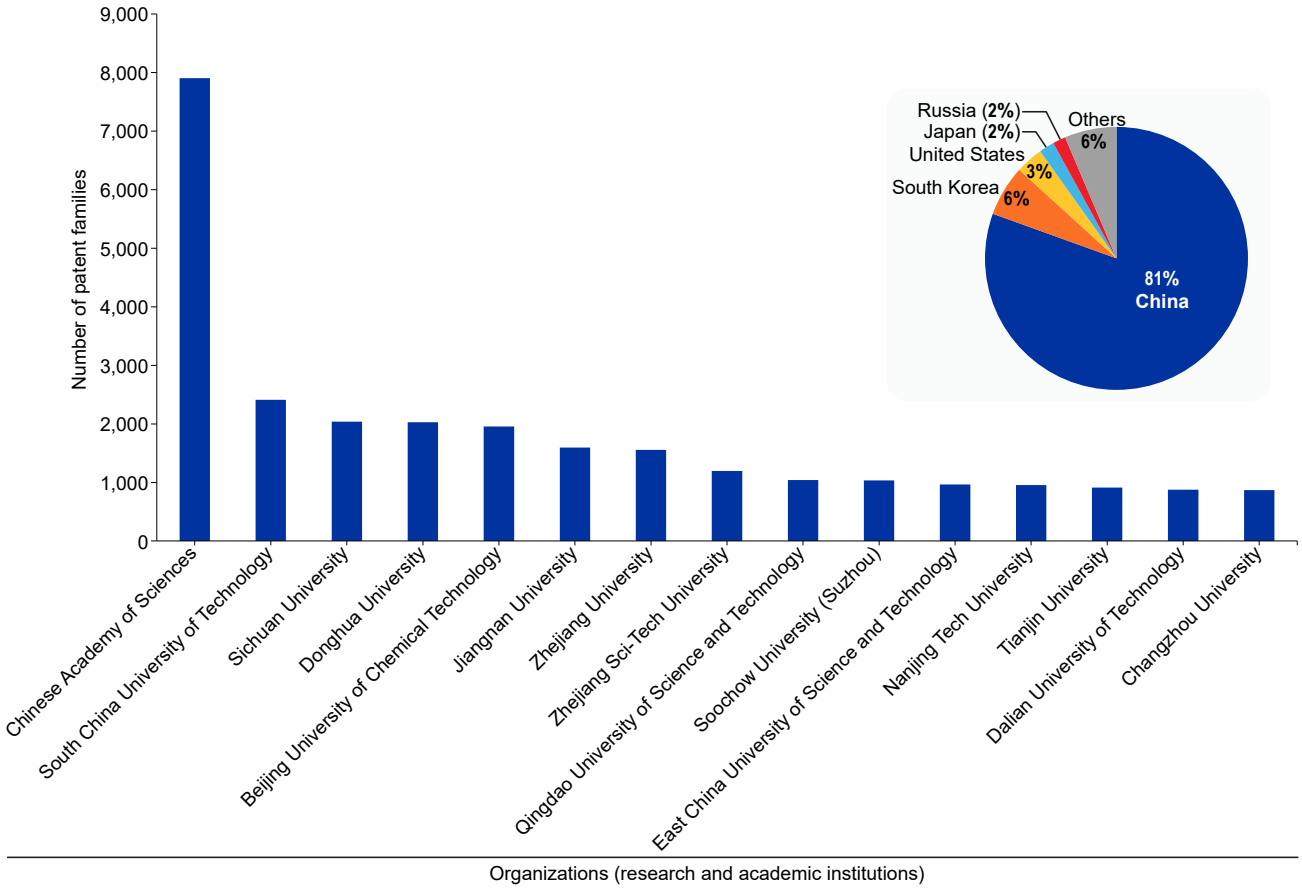


Figure 7. Leading organizations (research and academic institutions) in polymer research by number of patent families, with inset pie chart showing geographic distribution. Data includes patent families in the field of polymer research for the period 2015-2025 from the CAS Content Collection.

Sichuan University, Donghua University, and Beijing University of Chemical Technology each contribute 2,000-2,500 patent families, demonstrating systematic approaches to intellectual property creation within academic settings. This pattern suggests a research culture where patent filing is integrated into academic evaluation metrics and where universities maintain sophisticated technology transfer operations.

The relative absence of Western universities in top patent filing positions reveals fundamental differences in academic innovation models. While western institutions may excel in fundamental research and high-impact publications, they appear less focused on direct patent generation, potentially preferring licensing arrangements or spin-off companies for commercialization. The limited presence of other Asian universities, despite strong research outputs from countries like Japan and South Korea, suggests that commercial patent filing in these countries primarily occurs within industrial settings rather than universities.

The comparison of commercial versus non-commercial patent distributions across countries reveals distinct national innovation ecosystems and technology transfer mechanisms (**Figure 8**). China's dominance in commercial patents (280,000 families) is even more pronounced than in non-commercial patents (85,000 families), indicating that Chinese companies are actively translating polymer research into protected intellectual property at unprecedented scales. This 3.3:1 ratio of commercial to non-commercial patents suggests an innovation system where industrial R&D significantly outpaces academic patenting, despite high absolute numbers in both categories.

Japan shows a markedly different pattern with approximately 120,000 commercial patent families but minimal non-commercial patent activity. This 40:1 ratio indicates an innovation ecosystem where patent filing is almost exclusively an industrial activity, with universities potentially focusing on fundamental research while leaving commercialization to corporate partners. South Korea and the United States demonstrate intermediate patterns, with commercial patents exceeding non-commercial by factors of 5-10, suggesting more balanced but still industry-dominated innovation systems.

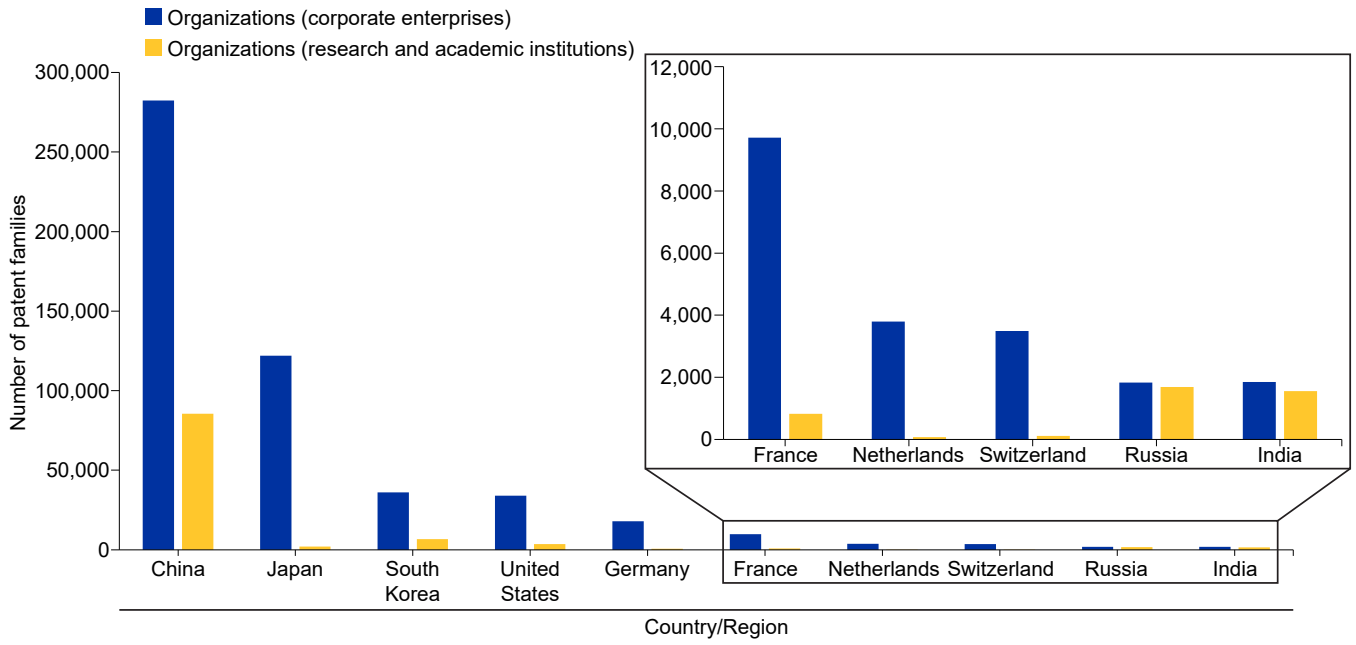


Figure 8. Distribution of research and academic organizations and corporate organizations patent families by country/region, with inset showing detail for selected countries (2015-2025).

European countries show interesting variations in the balance between commercial and non-commercial patenting activity. France demonstrates strong commercial patent activity relative to its size, while maintaining modest academic patenting. The Netherlands and Switzerland show commercial strength despite smaller absolute numbers, reflecting specialized innovation capabilities in high-value polymer applications. Russia and India present emerging patterns, with India showing surprising parity between commercial and non-commercial patents, suggesting a developing innovation ecosystem where academic institutions play significant roles in technology development.

Implications for Global Polymer Innovation

The bibliometric analysis reveals a polymer innovation landscape undergoing fundamental geographic and structural shifts. The overwhelming dominance of Chinese institutions in both publications and patents represents a historic transformation in global materials science, with implications for supply chains, technology standards, and innovation trajectories. The concentration of patent activity in Asian countries, particularly in commercial settings, suggests that the center of gravity for polymer innovation has decisively shifted eastward.

The high ratio of patents to journal publications across the field indicates a mature technology area where commercial applications drive research priorities. This commercially-oriented landscape may influence the types of polymer innovations pursued, potentially favoring incremental improvements and application-specific developments over fundamental breakthroughs. However, the presence of high-impact research from diverse global institutions suggests that transformative innovations continue to emerge from focused research efforts.

The distinct national patterns in innovation strategies—from China's volume-based comprehensive approach to Singapore's high-impact focused strategy—indicate that multiple models can succeed in polymer research. Organizations seeking to compete in this landscape must understand these different innovation ecosystems and adapt their strategies accordingly, whether through collaborative partnerships, strategic geographic positioning, or specialized capability development.

The data also reveals potential opportunities in underrepresented areas. The relatively limited patent activity from Western companies and universities, despite their historical strength in polymer science, might indicate untapped potential for technology transfer and commercialization. Similarly, emerging economies showing growing publication numbers but limited patent activity represent potential future growth areas as their innovation ecosystems mature.

This comprehensive analysis of polymer research trends provides essential context for understanding the current state and future directions of the field. As subsequent chapters explore specific application areas and emerging technologies, these broad patterns of geographic concentration, commercial dominance, and institutional diversity will provide crucial background for interpreting more detailed findings.

3.2 Comparative NLP-Driven Analysis of Academic and Commercial Polymer Innovation

Using NLP-based analysis we examined nearly 948K documents (journal and patent publications) with an aim to identify emerging and fast-growing scientific topics in the field. The identified emerging scientific topics were arranged in several CAS TrendScape maps (**Figures 9**-**18**) intended to provide large amounts of information including metrics of research interest and growth in a concise manner. Since the analysis was focused on identifying emerging topics, already well-established topics with no growth in scientific interest are unlikely to be identified.

The identified emerging concepts were clustered into 8 main branches, each representing a broad area of interest in Polymer research –

Polymer Types and Materials, **Composites and Nanocomposites**, **Applications and End-Use**, **Sustainability and Circular Economy**, **Fillers and Additives**, **Chemistry and Synthesis**, **Processing and Manufacturing**, **Properties and Performance**. Each of these 8 main branches were further divided into several layers of weighted sub-branches to give a granular view of emerging topics in the field. Scientific interest was represented by hexagons of increasing sizes representing number of publications ranging from >20 to >25K publications. The hexagonal nodes are also colored according to their average fold increase, as indicated in the inset legend, with warmer colors (red, orange, yellow) representing faster growth.

While journal and patent publications share similar emerging topics (**Figures 9** and **10**) at a broader level, especially evident for the **Polymer Types and Materials**, **Applications and End-Use**, and **Sustainability and Circular Economy** branches, notable differences exist in the quantity and nature of these topics (**Figures 11**-**16**). These differences can be attributed to the differences in journal and patent publications, the former is focused on reporting newer, more exploratory work performed by academic researchers in the field, while the latter is frequently focused on employing established materials and methods across applications with commercial interests.

Key points from comparison between journal and patent NLP data (**Figures 9** and **10**):

- **Polymer Types and Materials**: Biodegradable polymers, polyesters, and specialty polymers appear prominently in both domains, indicating broad research-to-application translation. Conductive polymers and complex architectures show significant academic research interest.
- **Composites and Nanocomposites**: Emphasis on aerogels, foams and other nanocomposites, specialized architecture, and membrane materials and systems across both academic research and patents.
- **Applications and End-Use**: Energy storage, electronic applications, and biomedical uses are emphasized in patent filings corresponding to larger volumes of patents.
- **Sustainability and Circular Economy**: Sustainability appears as a growing theme in both journal and patent publications, with recycling and circular economy concepts gaining prominence.
- **Fillers and Additives**: Patents concentrate on functional additives and practical reinforcements with clear commercial applications. Bio-based additives appear in academic research but less prominently in patents, suggesting an emerging opportunity area.
- **Chemistry and Synthesis**: Academic research covers broad fundamental chemistry with emphasis on reaction mechanisms. The patent landscape reveals stronger focus on practical synthesis aspects including initiators and crosslinking agents. Both domains prioritize catalysts, indicating their critical importance across research and application.
- **Processing and Manufacturing**: Patents show significantly more diverse manufacturing considerations including equipment and quality control. Journal publications feature more specialized and novel processing methods like self-assembly. The gap suggests potential opportunities for technology transfer from innovative academic processing to industrial applications.
- **Properties and Performance**: Self-healing appears prominently in academic research but less so in patents, indicating an emerging technology. Patents demonstrate stronger focus on practical properties like barriers and economic considerations. Both domains emphasize electrical, mechanical and thermal properties, showing alignment on core performance metrics.

3.2.1.Overall Research Themes in Polymer Science from Journal Landscape Analysis

The comprehensive CAS TrendScape map shown in **Figure 11** reveals interesting research trends within academic polymer science.

The surge in bio-based and bio-inspired polymers (1.2X) and biodegradable polymers (1.1X), in the **Polymer Types and Materials** branch, reflects the field's shift toward sustainable alternatives without compromising performance.[12] Adaptive and self-healing polymers (1.2X) are also emerging, offering autonomous repair capabilities that extend material lifespans and reduce maintenance costs.[13] The integration of conductive polymers (1.1X) with complex architectures (1X) is revolutionizing smart material applications.[14, 15] Polyimides known for their thermal stability, mechanical robustness, and chemical inertness

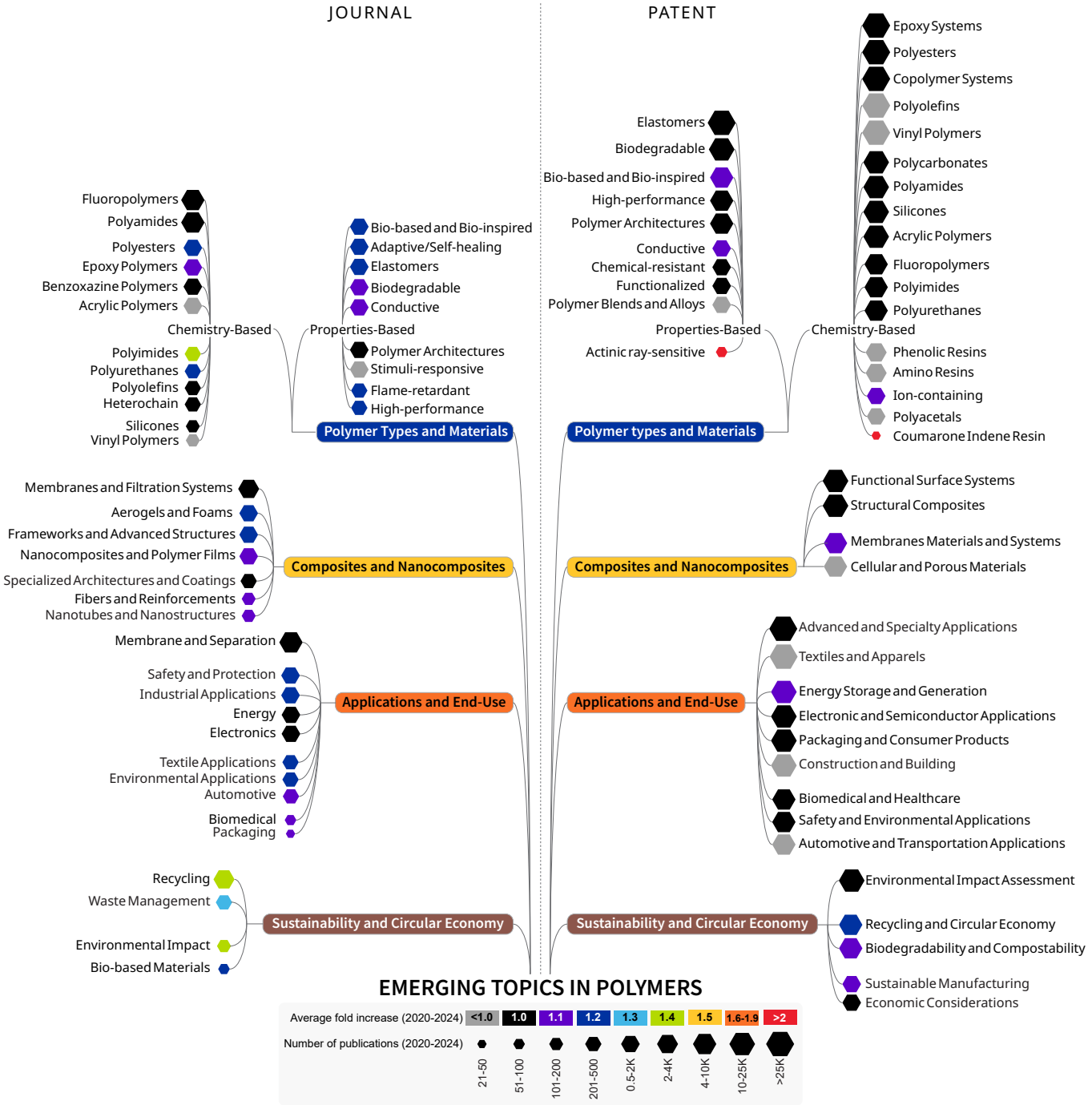


Figure 9. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of journal and patent publications focused on 4 of the major branches – **Polymer Types and Materials**, **Composites and Nanocomposites**, **Applications and End-Use**, and **Sustainability and Circular Economy**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

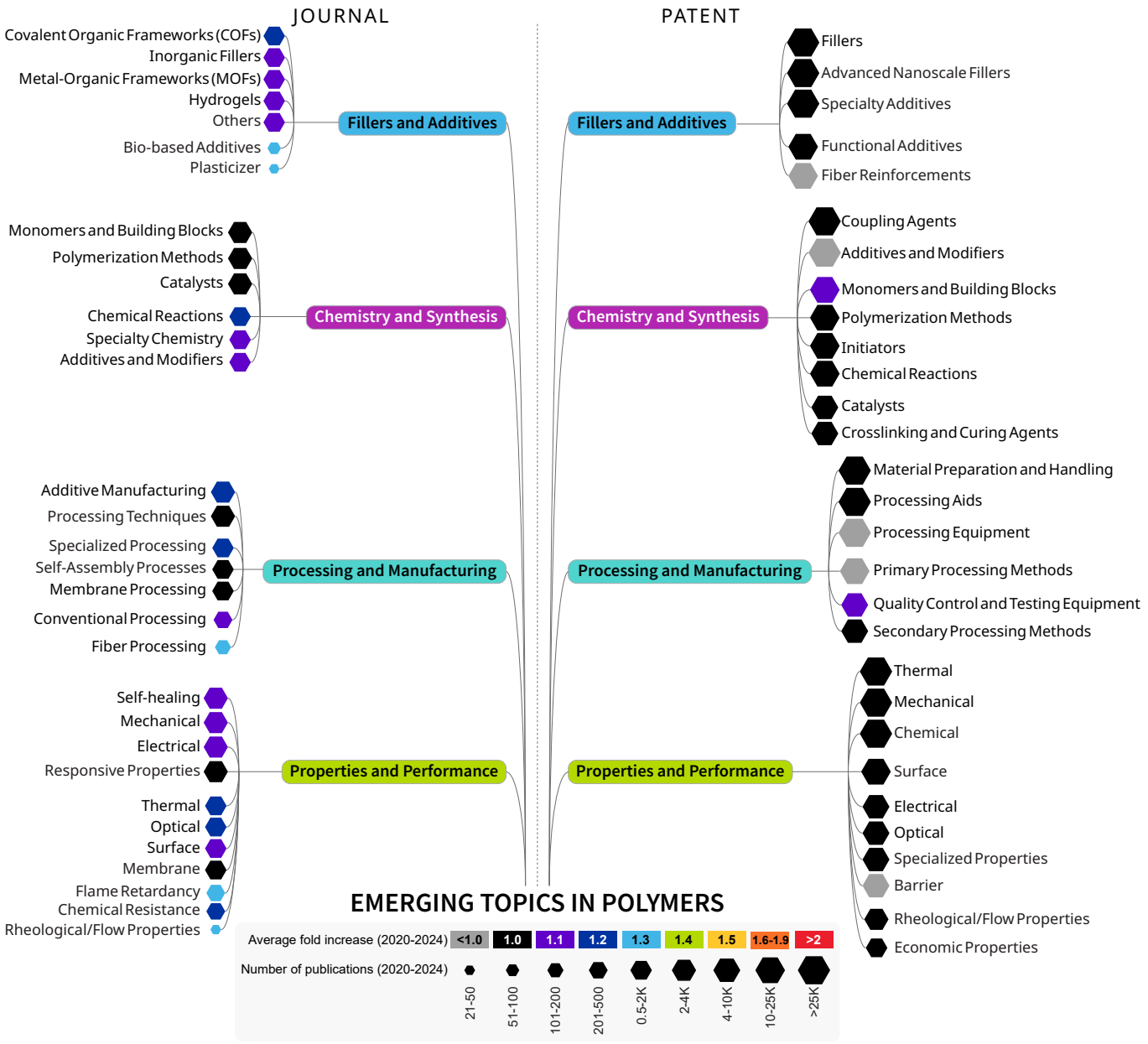


Figure 10. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of journal and patent publications focused on 4 of the major branches – **Fillers and Additives**, **Chemistry and Synthesis**, **Processing and Manufacturing**, and **Properties and Performance**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

appear to be emerging at a brisk pace (1.4X) possibly propelled by any number of factors: ultra-low dielectric polyimides are becoming essential for next-generation semiconductor packaging and flexible circuit boards,[16, 17] polyimide-based components in lithium-ion batteries (LIBs)[18] and humidity sensors[19] in electric vehicles, use of polyimides in flame-retardant systems[20] including textile,[21] polyamide aerogels with applications in thermal insulation,[22] etc.

In the **Chemistry and Synthesis** branch, specialty chemistry approaches yielding novel monomers and building blocks that enable previously impossible material properties appear to be emerging. Advanced polymerization methods, including controlled radical polymerization[23] and ring-opening metathesis polymerization (ROMP),[24] are facilitating precise molecular architecture control. The development of catalytic systems especially enzyme catalysts

(1.2X),[25] organocatalysts (1.1X)[26] and specialty catalysts (1.1X) for sustainable polymer synthesis is noteworthy, offering pathways to reduce environmental impact[27] while trying to maintain industrial scalability.

The **Composites and Nanocomposites** branch consists of several high-growth research areas, with nanotubes and nanostructures (1.1X) showing exceptional promise for multifunctional applications.[28, 29] The integration of specialized architectures and coatings (1X) is enabling hierarchical material designs that mimic natural systems.

Several topics in the **Fillers and Additives** branch are experiencing rapid expansion, driven by the need for multifunctional polymer systems. Metal-organic frameworks (MOFs, 1.1X) and covalent organic frameworks (COFs, 1.2X) are emerging as revolutionary fillers, providing unprecedented control over porosity, selectivity, and responsiveness.[30, 31] These hybrid systems are particularly valuable for membrane applications[32] and energy storage technologies.[33] Bio-based additives are experiencing notable growth in interest (1.3X) as sustainable alternatives to traditional petroleum-derived compounds.[34]

The **Applications and End-Use** branch shows signs of robust diversification with several topics appearing to emerge at a brisk pace. The automotive industry's transition toward lightweight, high-performance materials is driving demand for specialized polymer solutions.[35] Energy applications, particularly in battery separators[36] and photovoltaic encapsulants,[37] are experiencing unprecedented research activity. Environmental applications, including water treatment[38, 39] and air purification systems,[40, 41] represent emerging high-impact areas where polymers are addressing global sustainability challenges.

Multiple fast-growing topics in **Sustainability and Circular Economy** branch indicate that these considerations are now integral to polymer research, with recycling technologies (1.4X) and waste management strategies (1.3X)[42,43] experiencing rapid growth. Bio-based materials development is accelerating (1.2X), driven by both environmental concerns and regulatory pressures.[12, 44] Life cycle assessment methodologies (environmental impact, 1.4X) are becoming standard practice, ensuring that new polymer technologies deliver genuine environmental benefits throughout their entire lifecycle.[45]

The **Properties and Performance** branch shows several moderate-growing topics indicating that optimization remains central to polymer advancement, with rheological/flow properties showing the highest growth trajectory (1.3X).[46] Self-healing capabilities (1.1X) are transitioning from laboratory curiosities to practical applications,[47] while mechanical property (1.1X) enhancement continues to be optimized.[12] Thermal management properties (1.2X) are increasingly critical for electronics applications,[48] driving research into thermally conductive yet electrically insulating polymer systems.[49]

Finally, additive manufacturing techniques in the **Processing and Manufacturing** branch growing briskly (1.2X) are revolutionizing polymer processing, enabling complex geometries and distributed manufacturing models.[50] Specialized processing methods (1.2X), including emulsion-templating[51] and melt-blown process,[52] are facilitating the creation of hierarchical structures with tailored properties. Fiber processing (1.3X) appears to be experiencing brisk growth with carbon fiber manufacturing emerging in particular.[53] Hybrid carbon fiber manufacturing through co-spinning of carbon precursors with functional polymers is enabling the production of fibers with integrated sensing capabilities, thermal management properties, and electromagnetic functionality.[54, 55] Advanced recycling technologies for carbon fiber recovery and reprocessing are becoming increasingly important as composite structures reach end-of-life.[56, 57] Pyrolysis-based carbon fiber recovery processes integrated with re-spinning and re-carbonization capabilities are enabling circular manufacturing approaches that maintain fiber performance through multiple use cycles, establishing new paradigms for sustainable advanced materials manufacturing.[58] Membrane

processing technologies are also growing (1X) driven by applications in water treatment[59] and gas separation[60] among others.

3.2.2.Overall Innovation Themes in Polymer Patent Landscape Analysis

The patent landscape of emerging topics reveals distinctive research trends within the polymer technology ecosystem that diverges from academic research trajectories (**Figures 11**-**13**). This patent analysis demonstrates the industrial sector's strategic focus on market-ready polymer applications with near-term commercial potential:

Biodegradable polymers and conductive polymers represent notable areas of convergence between patent and journal activities, indicating successful research-to-commercialization translation pipelines in these domains. The commercial sector appears to be effectively capitalizing on academic breakthroughs in these high-growth areas. Examples of patents about biodegradable polymers include development of flame-retardant poly(lactic acid) (PLA) composites[61] by The Boeing Company and COMAC Beijing Aircraft Technology Research Institute, biodegradable plastic comprising of polyhydroxyalkanoate (PHA) blends[62] and alkyl polyesters capable of degrading in less than 180 days[63] by Beyond Plastic and Akina Inc., respectively. In **section 5**, we examine in greater detail bio-based and biodegradable polymers.

Self-healing materials demonstrate similar patent activity (1.1X) relative to their academic research volume (1.1X), indicating keen commercialization interest potentially driven by clear market applications in high-value sectors like aerospace and electronics. Examples of patents revolving around self-healing polymers include self-healing hydrogels comprised of PEDOT:PSS and PVA for wearable devices such as electronic skin (E-skin) developed by Eli Lilly and Company[64] and self-healing anti-icing polymer composite coating for electronics in aviation and other fields comprised of polydimethylsiloxane (PDMS) and ferrous oxide nanoparticles[65] developed by scientists at the National Institute of Defense Technology Innovation, China.

Besides aerospace and electronics, self-healing polymers also have applicability in construction involving the development of self-healing fiber-reinforced concrete by scientists at Drexel University consisting of concrete mixed with polymers such as polyesters, poly(vinyl alcohol) (PVA), polyamides, aramids etc.[66] as well as in the biomedical context where the self-healing property is attractive for medical devices.[67]

Structural composites and functional surface systems, in the **Composites and Nanocomposites** branch, demonstrate disproportionately high patent intensity relative to their academic research presence, suggesting these technologies have progressed further along the commercialization continuum with established IP protection strategies.

Application-centric innovation pattern emerges prominently, with extensive branching across diverse end-use sectors (energy storage, electronics, packaging, biomedical). This contrasts with the more material-centric organization observed in journal publications, reflecting the industry's market-driven innovation approach versus academia's material discovery emphasis. Energy storage applications show remarkable diversification beyond traditional Li-ion technologies, with patents covering hydrogen storage,[68, 69] Na-ion systems,[70, 71] and specialized membrane technologies such as for carbon adsorption.[72] This diversification is less evident in journal publications, suggesting industry may be pursuing alternative energy storage pathways more aggressively than academia. Moreover, analysis of the patent assignees reveals that companies located/originating in Asian countries/regions chief among them China, South Korea and Japan appear to account for majority of patents related to energy storage applications. In **section 4**, we delve deeper into polymers in this area. Healthcare polymer technologies demonstrate sophisticated categorization across medical devices,[73,74] implants,[75, 76] antimicrobial applications[77] including beyond healthcare such as food packaging[78] and textiles,[79] and biomaterials, revealing a level of application specificity that

exceeds the broader biomedical categorizations observed in academic publications. Electronic applications exhibit extensive subcategorization focusing on display technologies,[80, 81] flexible electronics,[82, 83] and interconnect solutions,[84] areas that receive comparatively less structured attention in academic research despite their commercial significance.

The substantial patent activity in sustainability-related technologies (particularly biodegradable materials and recycling processes) suggests market recognition of regulatory drivers and consumer preferences, areas where academic research might benefit from increased commercial awareness. Examples of commercially pursued sustainability endeavors include trying to develop degradable polyethylene-based plastics,[85] halogen-free flame-retardant cables[86, 87] and environment-friendly thermal insulation[88] as well as efforts to optimize green synthesis of various precursors used in polymer synthesis such as terephthalic acid.[89] Besides these, other avenues of sustainability research are biomass-derived polymers such as polyethylene (PE)[90] and PVA.[91] Geographic distribution of patent assignees indicates that commercial sustainability initiatives in recent years (2020-2025) appear to be spear-headed majorly by companies based in China and other Asian countries/regions (Japan, South Korea, India) with United States lagging considerably behind.

Advanced nanoscale fillers exhibit remarkable commercial attention with extensive subcategorization (carbon nanostructures,[92] nanoparticles),[93] suggesting accelerated industrial implementation of nanotechnology compared to the broader, less commercially-focused exploration in academic publications.[94,95] Similarly, chemical additives particularly functional additives (flame retardants,[96, 97] performance enhancers)[98, 99] and MOFs[100] and COFs[101] show up in patent filings, revealing industry's formulation-oriented approach to polymer development. Natural fiber reinforcements show unexpected patent intensity across multiple categories (wood,[102] cotton,[103] protein-based[104]) indicating noticeable industrial interest in sustainable composite systems.[105, 106] This commercial prioritization of bio-based reinforcements represents an area of convergence with academic research priorities in sustainability.[107, 108]

Academic research demonstrates substantial focus on novel polymer synthesis methodologies[109, 110] and advanced polymerization techniques,[111, 112] yet these approaches show limited representation in patent filings, which instead emphasize specific applications of established polymer systems. This suggests a potential disconnect with academic priorities more attuned to synthetic innovation and while industrial priorities lay in practical implementation with economic considerations.

Property-performance relationship optimization demonstrates substantial patent activity, particularly in specialized properties (self-healing),[113, 114] responsive behaviors,[115-117] and surface characteristics (adhesion,[118, 119] wettability[120, 121]). The patent data reveals greater emphasis on translating fundamental material properties into specific performance metrics, an application-oriented approach less evident in academic research. Responsive property innovations demonstrate noteworthy patent activity across multiple stimuli-responsive categories (light,[122, 123] heat,[124, 125] pH[126, 127]), and phase-change,[128, 129] suggesting accelerated commercialization of smart materials.

Processing aids and equipment specifications demonstrate extensive patent coverage, with detailed subcategories across material preparation (mixing,[130, 131] conveying[132]) surface modification[133, 134] and processing equipment (extrusion,[135, 136] molding,[137, 138] coating[139]) aspects that receive comparatively limited attention in academic publications despite their critical importance to commercial viability.

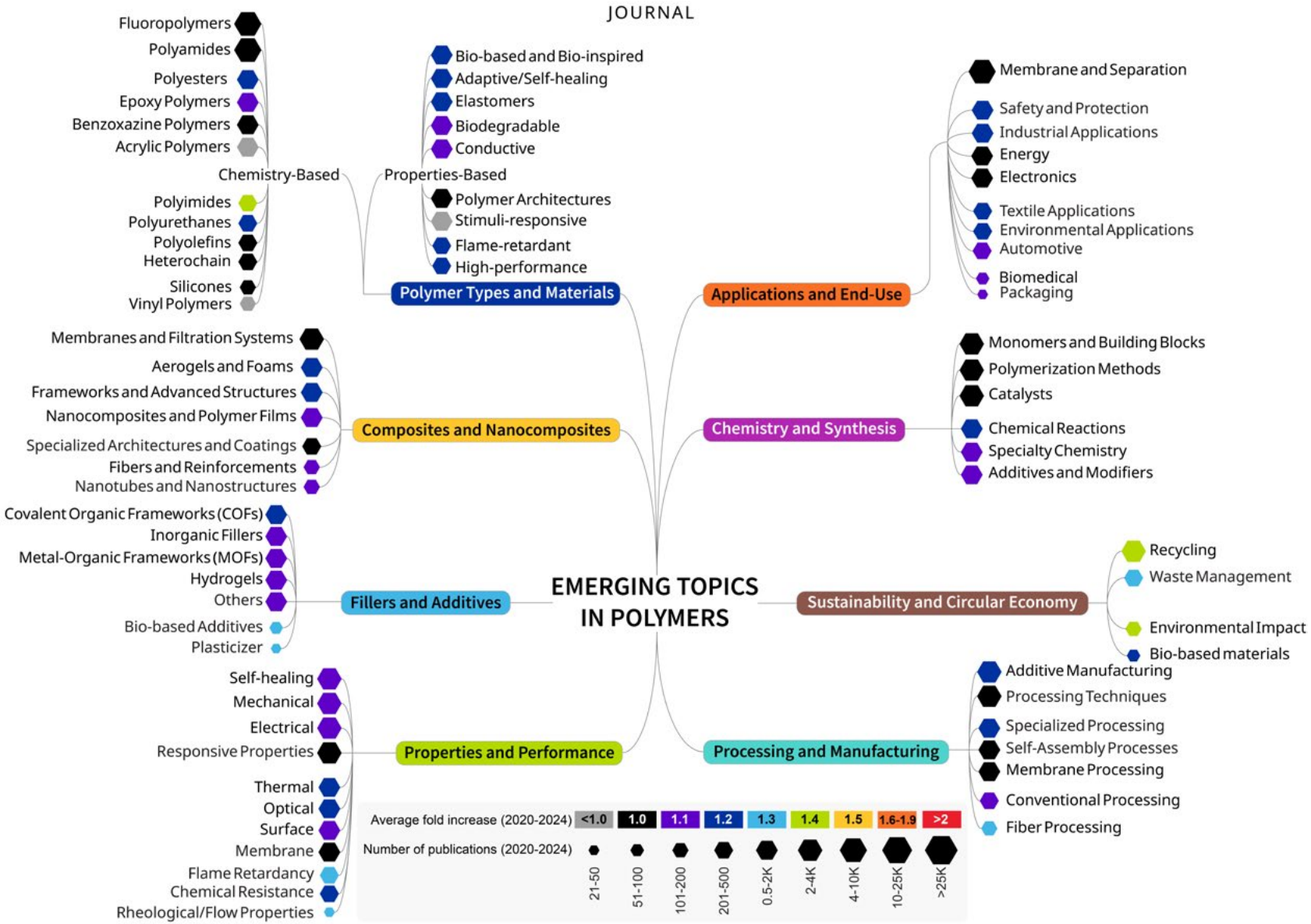


Figure 11. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of journal publications showing all 8 of the branches – **Polymer Types and Materials**, **Composites and Nanocomposites**, **Fillers and Additives**, **Properties and Performance**, **Applications and End-Use**, **Chemistry and Synthesis, Sustainability and Circular Economy**, and **Processing and Manufacturing**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

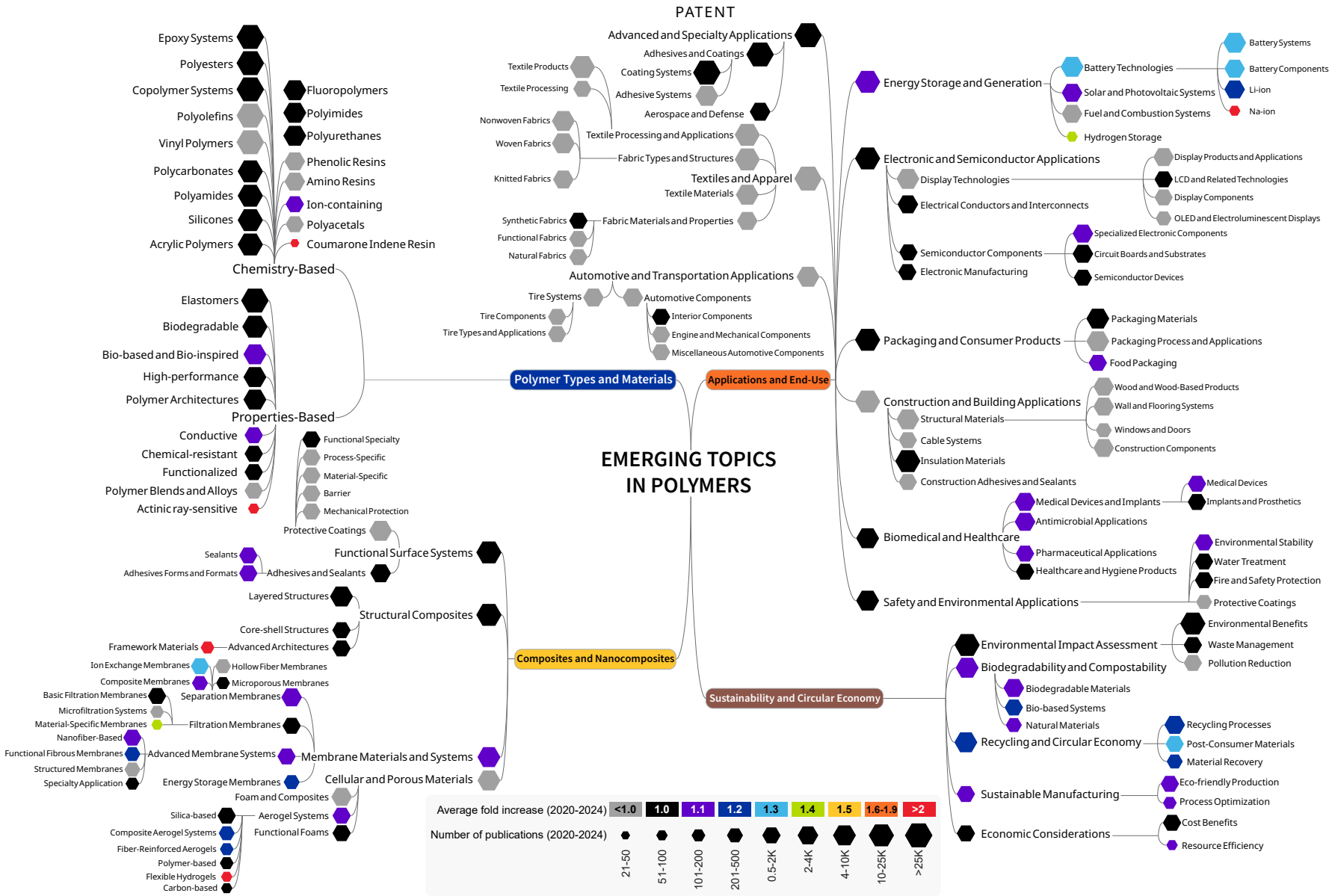


Figure 12. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of patent publications focused on 4 of the major branches – **Polymer Types and Materials**, **Composites and Nanocomposites**, **Applications and End-Use**, and **Sustainability and Circular Economy**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

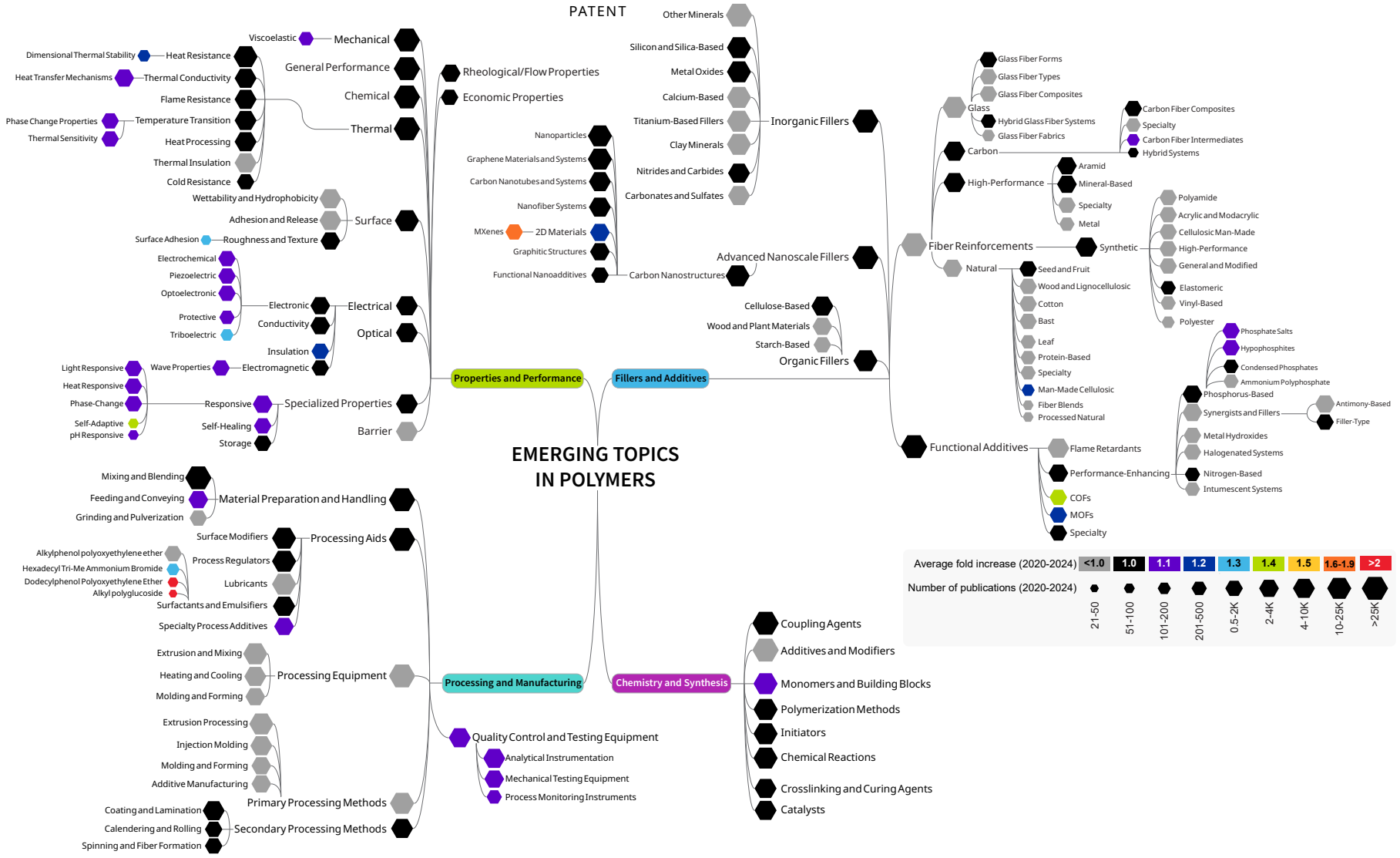


Figure 13. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of patent publications focused on 4 of the major branches – **Properties and Performance**, **Fillers and Additives**, **Processing and Manufacturing**, and **Chemistry and Synthesis**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

3.2.3.Emerging Trends in Polymer Types and Materials from Journal Landscape Analysis

The **Polymer Types and Materials** focused CAS TrendScape Map for NLP data based on journal publications (**Figure 14**) reveals varied areas of emergence, with several molecular architecture families demonstrating significant research intensity.

Carbon-backbone polymers with notable differentiation in substitution patterns and functional group incorporation show substantial research activity. Fluoropolymers demonstrate continued research interest with specific emphasis on polyvinylidene fluoride (PVDF) systems, likely driven by their piezoelectric properties[140] and energy storage applications.[141] The relatively modest research intensity in conventional vinyl polymers (PE, polystyrene) compared to functionalized variants[142] suggests a mature understanding of these systems with research now emphasizing post-synthetic modification and property enhancement strategies.

Polyesters emerge as particularly active research domains with significant diversification across furanoate-based systems (PEF, PPF, PBF) that incorporate bio-derived 2,5-furandicarboxylic acid.[143, 144] This research intensity aligns with sustainability imperatives for petroleum-independent polymer feedstocks. Similarly, polyurethanes demonstrate notable research emphasis on non-isocyanate synthesis routes (non-isocyanate polyurethane, NIPU)[145] and polyhydroxyurethanes (PHU),[22] reflecting movement toward addressing toxicity concerns in traditional urethane chemistry[146] while maintaining versatile property profiles.

Our NLP data reveal accelerated research trends in polymers with sophisticated architectural features, particularly heterochain structures, ionic polymers,[147] and conjugated systems.[148] This emphasis on complex architectures rather than simple linear systems indicates progression toward precision macromolecular engineering with tailored sequence distribution,[149] controlled tacticity,[150] and defined stereoregularity.[151] The emergence of polyoxazolines[152] and polysulfur[153] polymers as distinct subcategories demonstrates growing recognition of these architectures' unique property potential.

We also observe remarkable research intensity in bio-based systems spanning multiple structural categories. Notably, furanoate polyesters,[154] poly(propylene fumarate) (PPF),[155] and carbonate polymers[156] demonstrate high publication volumes, indicating successful integration of renewable monomers into established polymer architectures. The research emphasis on natural polymer systems (cellulose,[157] lignin,[158] etc.) further reflects the field's strategic pivot toward bio-derived macromolecules with inherent functionality. The substantial research activity in poly(lactic acid)/polybutylene adipate terephthalate (PLA/PBAT) blends[159, 160] and polyhydroxyalkanoates (PHAs) indicates focused efforts to overcome mechanical limitations of single-component biodegradable systems.[161] The emergence of poly(butylene succinate-co-adipate) (PBSA),[162] poly(butylene succinate-co-terephthalate) (PBST)[163] and poly(butylene succinate) (PBS)[164] as distinct categories suggests growing attention to alternative biodegradable polyester architectures beyond established PLA[165] and PBAT [166] systems.

Similarly, our analysis illustrates exceptional research momentum in polymers exhibiting dynamic behavior, particularly covalent adaptable networks (CANs),[167, 168] self-healing systems,[169] and liquid crystal elastomers (LCEs).[170] The high publication intensity in vitrimers[171] and CANs indicates growing interest in recyclable thermosets[172, 173] that combine mechanical robustness with reprocessability. Similarly, the prominent positioning of stimuli-responsive polymers reflects their versatility across applications requiring on-demand property modulation.[174] The parallel emphasis on complex architectures and responsive properties suggests growing understanding of molecular design principles that govern macroscopic behavior. This convergence facilitates more rational polymer design strategies rather than empirical optimization approaches.

Conductive polymers demonstrate sustained research with ionic conductive elastomers

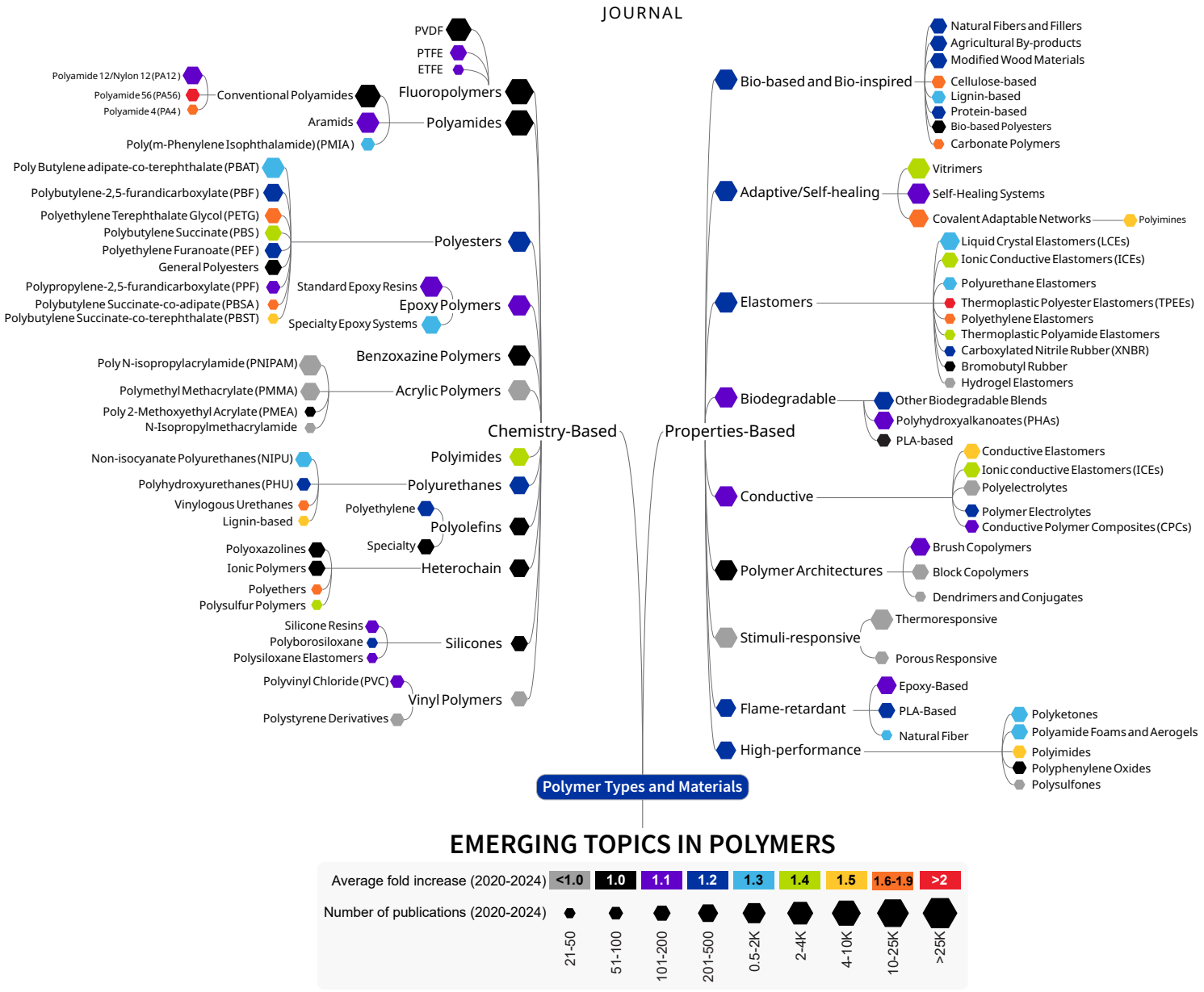


Figure 14. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of journal publications focused on one of the major branches – **Polymer Types and Materials**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

(ICEs),[175, 176] conductive polymer composites (CPCs),[177, 178] and polyelectrolyte multilayers (PEMs)[179] emerging as particularly active areas of research. Our CAS TrendScape maps reveal strategic emphasis on flexible electronic systems[180] where polymer conductivity offers advantages over traditional inorganic conductors. The presence of PBDB-T highlights the continued relevance of conjugated polymers in organic electronics.[181] Research activity in aromatic polyamides [182] and high-performance fibers[183] indicates continued interest in ultra-high-strength materials.

Our analysis demonstrates increased research attention to polymers that simultaneously address multiple property requirements (e.g., conductive elastomers, self-healing thermoplastics), reflecting application environments that demand property combinations previously considered incompatible. The substantial research activity in both bio-based chemistry and biodegradable properties indicates progress toward resolving the historical tension between environmental compatibility and functional performance, particularly through strategic copolymerization and blending approaches.

3.2.4.Emerging Trends in Polymer Types and Materials from Patent Landscape Analysis

The **Polymer Types and Materials** focused CAS TrendScape Map for NLP data based on patent publications (**Figures 15** and **16**) are substantially more populated with emerging topics/areas with commonality in the broader areas (such as polyesters, polyamides, polyurethanes, elastomers, conductive polymers etc.) but interesting differences within these and other broader categories indicating variations in priorities between academic and corporate research interests.

Polyesters: The prominent PLA systems cluster demonstrates substantial research consolidation around PLA platforms, with distinct subcategories including PLA blends,[184] PLA copolymers,[185] and modified PLA.[186] These emerging topics might be indicative of interest in approaches to addressing PLA's inherent limitations (brittleness[187, 188] thermal stability[189] through compositional modification and blend optimization.

The incorporation of functional comonomers (hydroxylated, halogenated, aromatic) expands material capabilities beyond conventional thermoplastic performance. Among the different PHA copolymers, representing distinct monomer combinations, poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH or PHBHHx) appears to be growing fastest (1.5X) followed by poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P(3HB-co-4HB), 1.3X) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV or P(3HB-co-3HV), 1.1X) (**Figure 15**), the latter serving as the archetypal PHA copolymer, with valerate incorporation systematically reducing crystallinity and melting point.[190] The methyl branch disruption of PHB's regular crystal packing enables processability enhancement while maintaining thermal stability.[191] Commercial success of PHBV copolymers demonstrates scalable fermentation control[192] and predictable property modulation.[192] PHBHHx represents a critical advancement in PHA property engineering, incorporating medium-chain-length monomers to disrupt PHB's inherent crystallinity. The hexanoate comonomer introduction reduces glass transition temperature and crystallization rate, addressing PHB's brittleness and narrow processing window.[193] Research demonstrates optimal flexibility-strength balance at 2-14 mol% HHx content, enabling applications requiring impact resistance with some reduction in biodegradability.[194] P(3HB-co-4HB) introduces positional isomerism through 4HB comonomer incorporation, creating distinct chain flexibility compared to 3HB units. The additional methylene unit in 4HB provides enhanced chain mobility and reduced intermolecular interactions. Research indicates superior elongation at break at optimal 4HB content,[195] positioning this copolymer for flexible packaging applications.

Epoxy Systems: Emergence of polyglycidyl compounds indicates research emphasis on multifunctional crosslinking architectures enabling enhanced crosslink density and

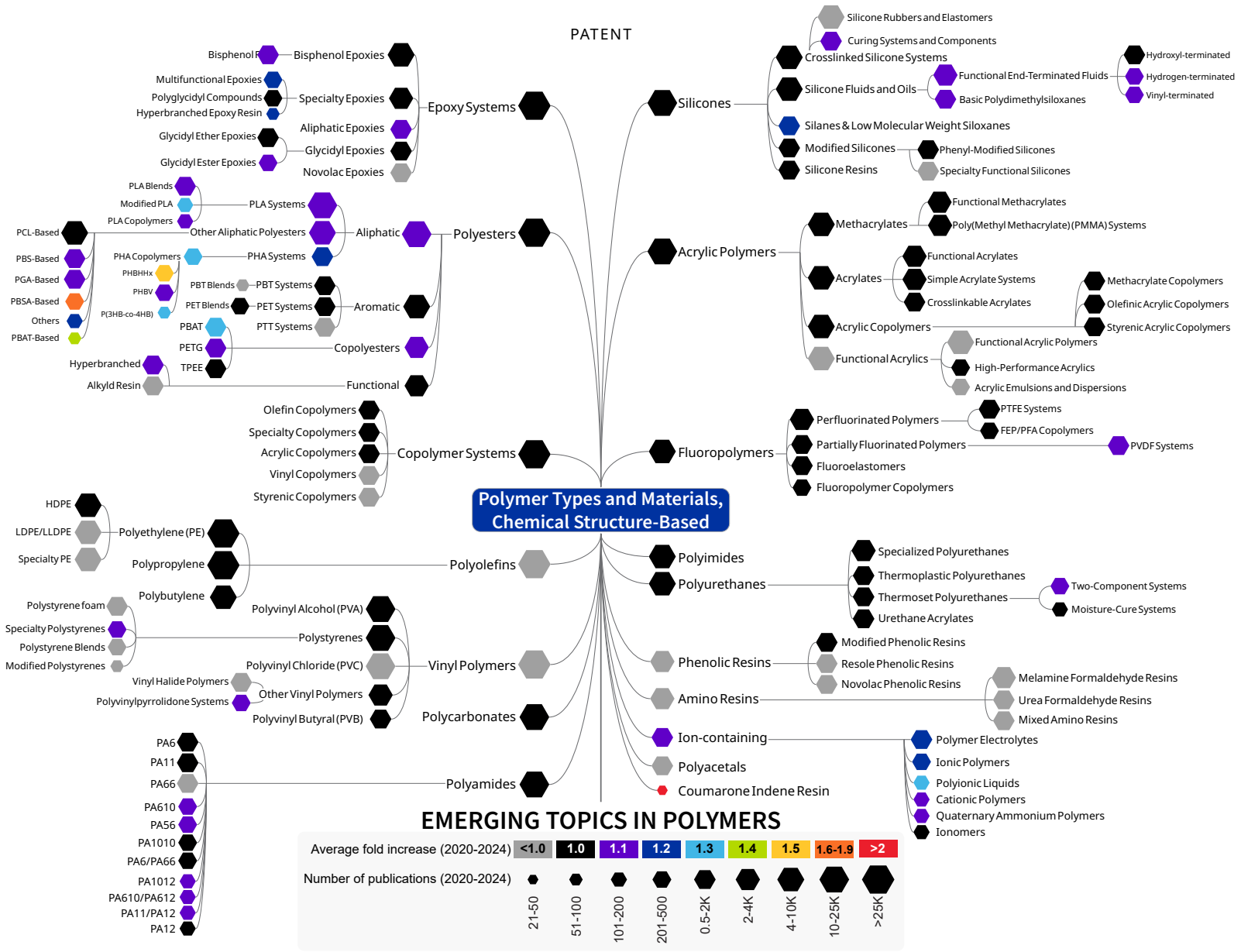


Figure 15. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of patents focused on one of the major branches – **Polymer Types and Materials** – with polymers being arranged/classified based on chemistry. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

thermal performance.[196] Similarly, emergence of hyperbranched epoxy resins[197, 198] demonstrates growing recognition of dendritic architectures for processability enhancement[199] and viscosity-related applications[200] while growing research interest in multifunctional epoxies applicable across diverse array of applications including energy-related,[201] electronics,[202] aerospace[203] and reflects systematic approaches to crosslink density optimization through controlled functionality incorporation. Bisphenol F (BPF) prominence[204] suggesting continued interest in developing health-conscious alternatives to bisphenol A (BPA)-based systems, reflecting regulatory pressure and toxicological considerations though reports suggest that BPF likely also possesses the same toxicological concerns as BPA.[205]

Silicones: Curing systems and components and crosslinked silicone systems represent critical research domains addressing processing-performance optimization. The prominence of curing chemistry research reflects industrial demands for controlled gelation kinetics, ambient temperature processing, and tailored network architecture. Interest in functional end-terminated fluids emphasize research on coupling agent development and surface modification applications with hydroxyl-terminated,[206] hydrogen-terminated,[207] and vinyl-terminated[208] systems representing distinct reactivity platforms for crosslinking control and chain extension. Emergence of topics related to silanes and low molecular weight siloxanes indicates fundamental building block research for controlled polymerization and network precursor development. Basic polydimethylsiloxanes (PDMS) serve as the reference architecture for comparative property analysis and modification strategies. Phenyl-modified silicones[209, 210] and specialty functional silicones[211, 212] demonstrate systematic approaches to property enhancement through side-chain modification and functional group incorporation enabling application-specific optimization while maintaining siloxane backbone advantages.

Ion-containing Polymers: Ion-containing systems demonstrate sustained research interest (~1.1X growth) with systematic functionality incorporation across diverse polymer backbones. Polymer electrolytes prominence as a high-growth node indicates strategic research focus on solid-state battery applications[213] and electrochemical devices[214] with the ~2-4K publication volume suggests mature research infrastructure with systematic optimization of ionic conductivity, mechanical stability, and electrochemical windows. Cationic polymers[215, 216] and quaternary ammonium polymers (polyQAC[217]) represent pendant ionic functionality, while ionomers[218] incorporate ionic domains within neutral polymer matrices. This architectural distinction enables tailored ion transport mechanisms and mechanical property control. Polyionic liquids,[219, 220] emergence as a distinct research category reflects advanced materials integration combining polymer processing advantages with ionic liquid properties with the moderate growth trajectory (1.3X increase) suggesting developing research maturity in this hybrid architecture domain.

Bio-Based and Bio-Inspired Systems: Bio-based and bio-inspired polymers demonstrate exceptional research momentum with some topics showing growth as high as ~1.5X growth (**Figure 16**) driven by sustainability imperatives and feedstock diversification strategies. Bio-based engineering polymers such as polyurethanes,[221, 222] polyamides,[223, 224] and polyesters[225, 226] all appear to be growing at a very brisk pace of (>1.3X). Plant-based materials show moderate growth (1.1X) but considerable publication volume (2-4K), indicating continued research interest with possibility of transitioning toward commercial scalability.

Biodegradable Polymers: Biodegradable fibers[227] represent a critical growth sector (1.5X increase) addressing textile waste management[228, 229] and marine pollution mitigation.[230] Research intensity focuses on PLA-based systems[231] with enhanced mechanical properties[165, 232] through chain extension,[233, 234] nucleation control,[235, 236] and orientation optimization.[237, 238] Biodegradable thermoplastics show sustained growth (1.3X) with emphasis on processing-performance balance for packaging

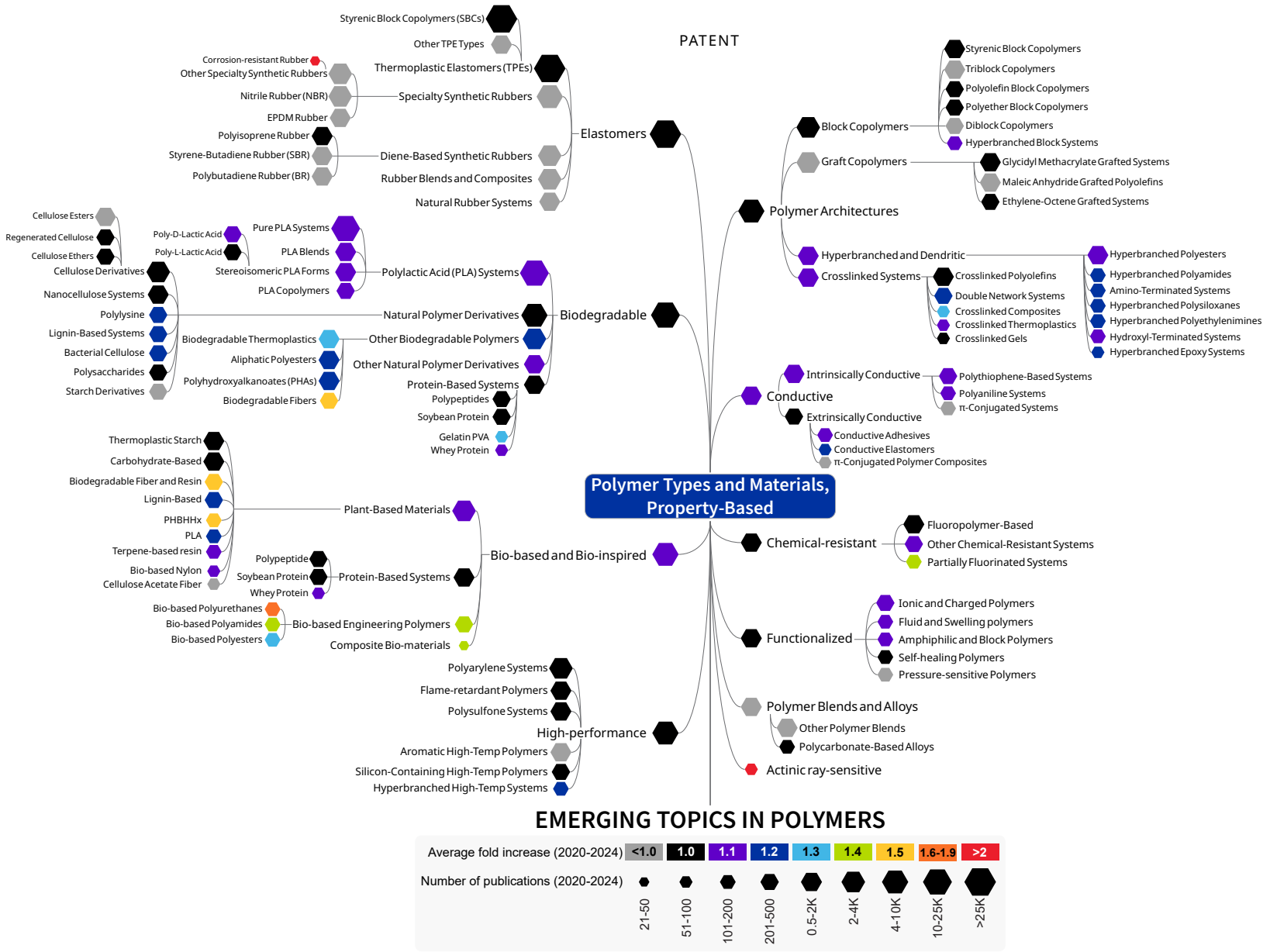


Figure 16. CAS TrendScape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of patents focused on one of the major branches – **Polymer Types and Materials** – with polymers being arranged/classified based on their properties. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

applications.[239, 240] In Section 5, we present our findings from a detailed and comprehensive analysis of bio-based and biodegradable polymers.

Complex Architectures: Complex architectures emerge as a high-growth domain (>1 to 1.3X) with crosslinked systems and hyperbranched and dendritic structures[241, 242] leading in terms of research interest. Crosslinked systems demonstrate modest publication volume (>1K) indicating increasing understanding of network topology control for targeted property optimization. [243, 244] Hyperbranched polyamides[245, 246] and polyesters[247, 248] show modest growth reflecting processing advantages and functionalization potential.

Other Polymers: Conventional vinyl polymers, acrylic polymers and fluoropolymers show modest research interest, suggesting research saturation. Phenolic resins maintain steady research presence, likely due to high-performance applications.[249-251] Within Elastomers, specialty synthetic rubbers research emphasizes chemical resistance enhancement through fluoropolymer integration[252] and crosslink optimization.[253] Corrosion-resistant rubber systems demonstrate fast (>2X) growing though limited research interest(~23),[254,255] with thermoplastic elastomers (TPEs) showing significant publication volume but slow growth (~1X). Styrene-butadiene rubber (SBR) maintains steady research trajectory focusing on morphology control and service life extension.[256,257]

Analysis of polymer research trends reveals distinct patterns between academic journal publications and patent filings, indicating different priorities in fundamental research versus commercial development. Journal landscape analysis demonstrates strong academic focus on sophisticated molecular architectures, particularly complex systems like covalent adaptable networks, self-healing polymers, and stimuli-responsive materials that exhibit dynamic behavior and precision macromolecular engineering. Academic research emphasizes bio-based sustainability solutions including furanoate polyesters (PEF, PPF, PBF), NIPU, and natural polymer systems, while also pursuing advanced conductive polymers for flexible electronics and multifunctional materials that combine previously incompatible properties. In contrast, patent landscape analysis shows substantially more populated emerging areas with greater commercial focus on scalable solutions, particularly around PLA platform technologies and PHA copolymers with specific growth trajectories (PHBHHx at 1.5X, P(3HB-co-4HB) at 1.3X). Patent activity emphasizes practical applications including epoxy systems for industrial crosslinking, silicone curing technologies, ion-containing polymers for battery applications, and biodegradable fibers addressing textile waste (1.5X growth). Most significantly, both landscapes demonstrate exceptional momentum in bio-based and biodegradable systems, with patent data showing bio-based engineering polymers growing at >1.3X rates, indicating successful translation of academic sustainability research into commercial development priorities.

3.2.5.Chemistry and Synthesis Divergence: Academic Discovery vs. Commercial Implementation

The journal CAS TrendScape map (**Figure 17**) demonstrates clear academic research priorities focused on fundamental polymer chemistry and mechanistic understanding. Catalysts,[258,259] polymerization methods,[260,261] and chemical reactions[262] dominate the emerging research landscape with considerable publication volumes (~0.5-4K), reflecting systematic investigation of reaction mechanisms and synthetic methodology development. Conversely, the patent landscape emphasizes commercial implementation through greater diversification of additives and modifiers,[263-265] coupling agents,[266, 267] and crosslinking,[268, 269] and curing agents,[270, 271] indicating industrial focus on performance optimization and processing enhancement (**Figure 18**).

In terms of polymerization methods, journal research exhibits higher growth rates in emerging methodologies: ring-opening polymerization[272, 273] and radical polymerization[274, 275] show >1.1X

increases, suggesting academic exploration of novel synthetic approaches. Patent research demonstrates greater diversity in polymerization methods with mostly conservative growth patterns in established technologies (bulk, imprint, and emulsion polymerization) with moderate publication volumes (up to 2K), reflecting industrial risk aversion and proven technology scaling. Patent landscape prioritizes scalable processing methods (suspension polymerization)[276, 277] and industrial equipment (reactor-based systems[278, 279]), reflecting manufacturing optimization priorities. The emergence of photopolymerization[280, 281] (1.2X) alongside established methods indicates industrial interest, particularly relevant for: 3D printing[282] and additive manufacturing applications,[283] coating,[284] adhesives,[285] electronics[286] and semiconductor processing.[287]

Academic research shows strategic emphasis on sustainable chemistry and bio-based monomers and building blocks[288, 289] with moderate growth (~1.2X), indicating possible long-term research investment in environmental compliance. The journal CAS TrendScape map (**Figure 17**) also exhibits sophisticated chemical diversity through specialty chemistry,[290, 291] functional chemistry,[292] and cyclic monomers,[293, 294] reflecting academic freedom to explore complex molecular architectures. Patent research shows practical specialization in established chemical families (aromatic and vinyl monomers) and performance additives (UV protection, antioxidants), indicating commercial focus on proven material platforms.

The patent emphasis on stabilizers and protectants,[295] plasticizers,[296] and coupling agents reveals market-responsive research addressing immediate industrial needs. Journal research maintains discovery-oriented focus on bond formation/exchange[297, 298] and degradation reactions,[299, 300] indicating academic commitment to fundamental understanding independent of immediate commercial applications. Patent landscape reveals limited sustainability focus, with conventional processing methods dominating, suggesting industrial lag in green technology adoption due to economic constraints and infrastructure limitations.

Academic research emphasizes advanced polymerization control through Specialty Catalysts[301] (1.1X) and Metal Catalysts[302] (1X) with high publication intensity, suggesting continued fundamental discoveries in catalytic mechanisms. Emergence of organocatalysts[303] (1.1X) and enzyme catalysts[304] (1.2X) reflects the field's pivot toward sustainable synthesis methodologies. The patent landscape reveals a more pragmatic emphasis on curing catalysts[305] (1.1X), reflecting industrial prioritization of processable systems with commercial scalability. The prominence of tin-based (1X),[306, 307] and other metal catalysts (iron, platinum, titanium),[308-310] in patent filings indicates continued industrial reliance on established organometallic systems despite academic movement toward metal-free alternatives, suggesting a lag between academic innovation and industrial implementation. The patent activity in isocyanate curing systems[311] (1.2X) and condensation catalysts[312] (1.1X) reflects mature industrial infrastructure around established polyurethane and polyester technologies, where incremental catalytic improvements drive competitive advantage.

Academic research demonstrates clear emphasis on fundamental polymer chemistry, mechanistic understanding, and emerging methodologies, with catalysts, polymerization methods, and chemical reactions dominating the research landscape alongside strategic focus on sustainable chemistry, bio-based monomers, and advanced catalytic systems including organocatalysts and enzyme catalysts that represent the field's pivot toward environmentally conscious synthesis. Patent research conversely prioritizes commercial viability through greater diversification of additives, modifiers, and processing agents, emphasizing scalable technologies with conservative growth patterns in established polymerization methods (bulk, emulsion, suspension) and practical specialization in proven chemical families and performance additives. This divergence is particularly evident in catalysis, where academic research explores metal-free alternatives and sophisticated catalytic architectures while industrial patents maintain reliance on established organometallic

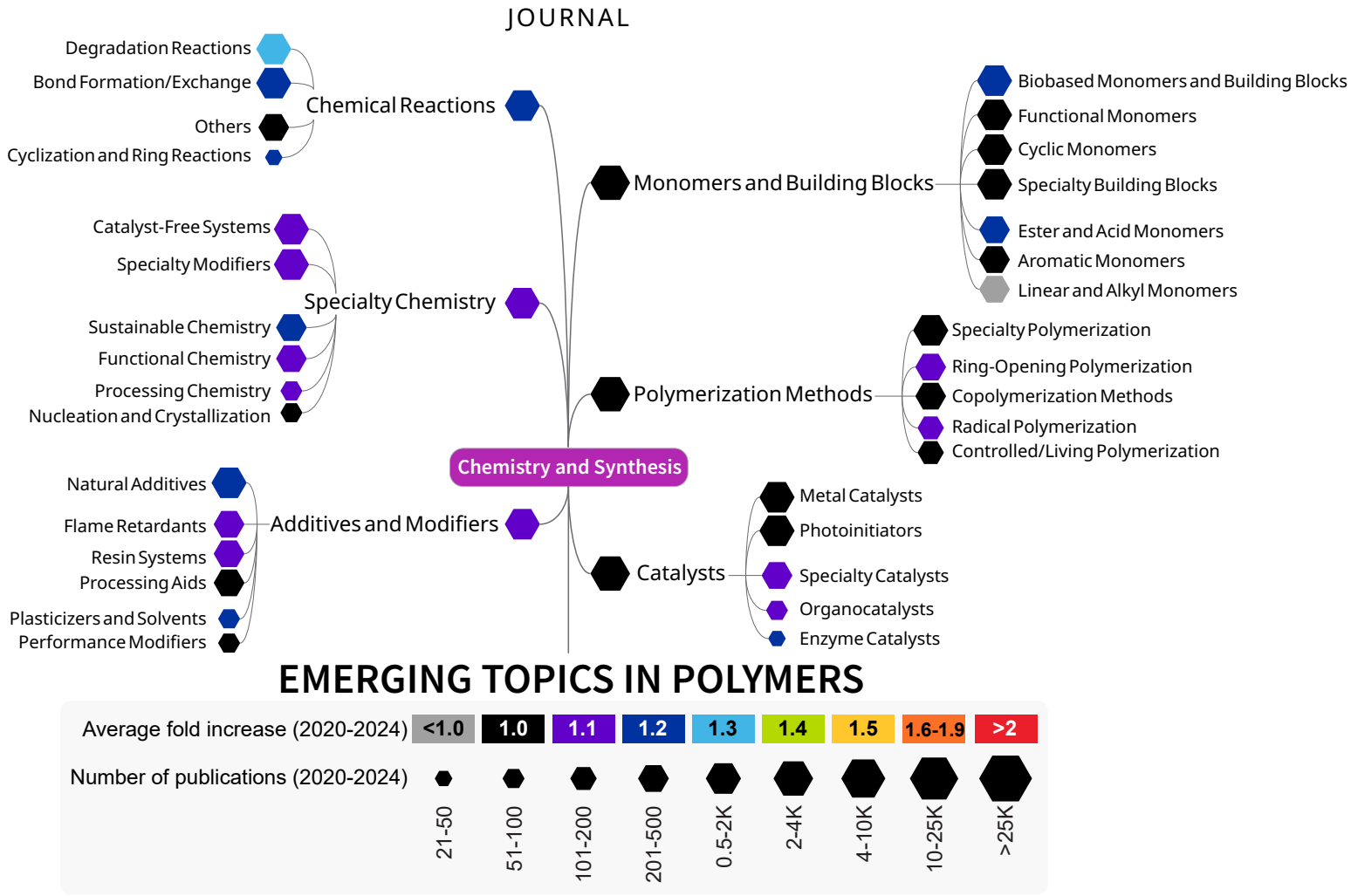


Figure 17. CAS Trendscape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of journal publications focused on one of the major branches – **Chemistry and Synthesis**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

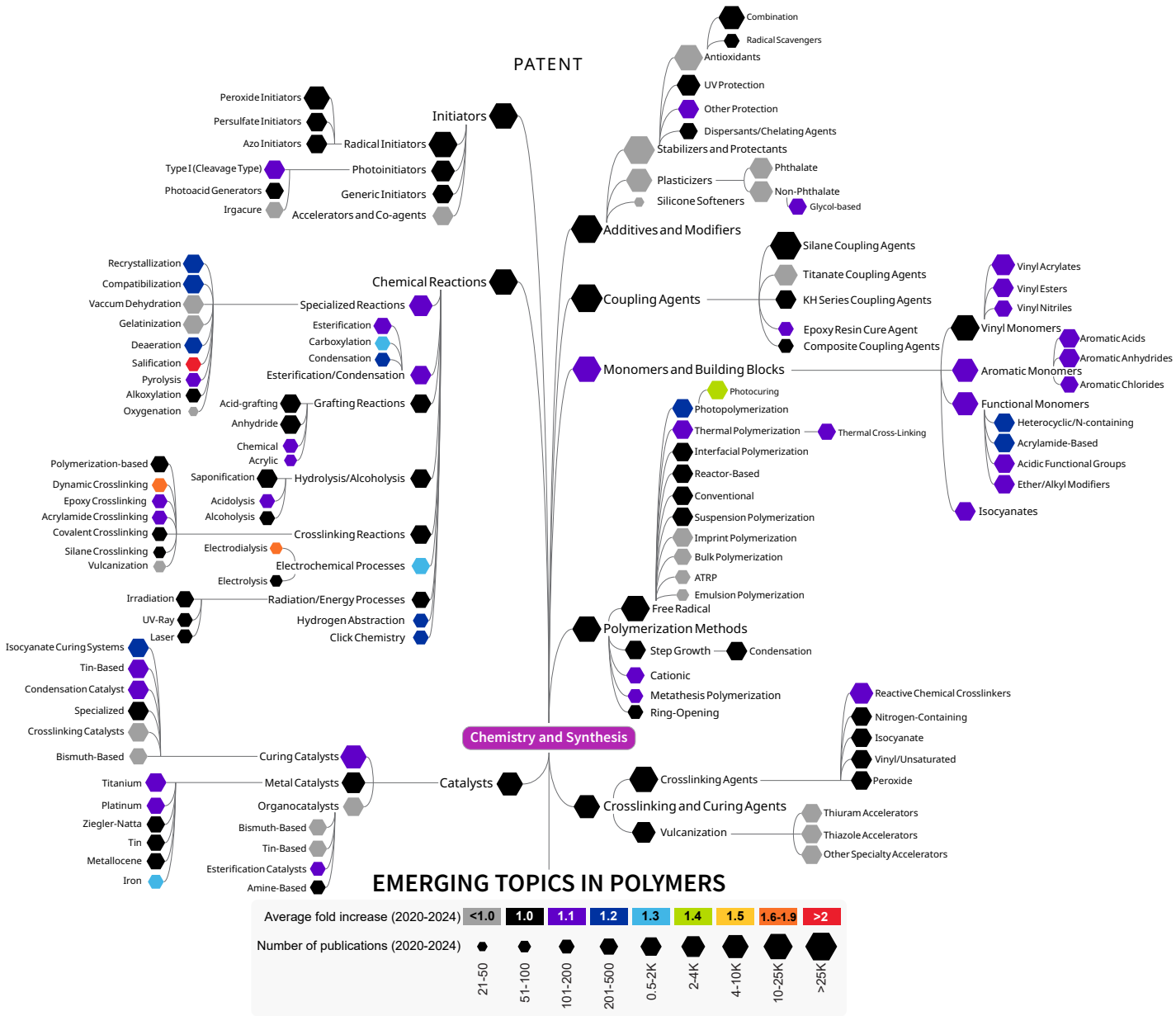


Figure 18. CAS Trendscape map of emerging topics in polymers based on natural language processing (NLP)-based analysis of patent publications focused on one of the major branches – **Chemistry and Synthesis**. The size of the hexagon indicates overall research interest (number of publications) while the color is indicative of growth in publications (fold increase) with warmer colors indicating faster growth.

systems, reflecting a lag between academic innovation and commercial adoption likely driven by economic constraints and infrastructure limitations. The analysis reveals that while academic research maintains discovery-oriented focus on bond formation mechanisms and degradation reactions independent of immediate commercial applications, patent activity demonstrates market-responsive research addressing immediate industrial needs through performance optimization and processing enhancement, suggesting that successful technology transfer requires bridging the gap between fundamental scientific advances and scalable manufacturing realities.

Our comprehensive analysis of nearly 1 million publications led to identification of emerging topics in polymers across eight major branches each exhibiting distinct growth trajectories and innovation patterns across academic and industrial domains. Academic research demonstrates emphasis on sophisticated molecular architectures and fundamental breakthroughs, with remarkable momentum in bio-based and biodegradable systems, complex architectures including covalent adaptable networks and self-healing polymers, and advanced catalytic systems featuring organocatalysts and enzyme catalysts representing the field's pivot toward sustainable synthesis. The journal landscape reveals strategic focus on precision macromolecular engineering, stimuli-responsive materials, and multifunctional systems that combine previously incompatible properties, while maintaining discovery-oriented investigation of reaction mechanisms independent of immediate commercial viability.

Commercial patent activity conversely prioritizes scalable solutions with market-ready applications, showing substantially more populated emerging areas focused on practical implementation. Patent research emphasizes established polymer platforms with systematic optimization, particularly PLA systems and PHA copolymers alongside extensive diversification in performance additives, processing aids, and application-specific formulations. Industrial priorities center on proven technologies with conservative growth patterns, equipment optimization, and market-responsive solutions addressing immediate commercial needs.

Critical convergence opportunities emerge in sustainability-focused innovations, where both academia and industry demonstrate noteworthy research momentum in biodegradable polymers and bio-based engineering systems, indicating successful translation pathways from academic research to commercial development. However, significant translation gaps persist, particularly in advanced synthesis methodologies, complex architectures, and metal-free catalytic systems, where academic innovations show limited patent representation despite demonstrated technical advantages.

Our analysis provides critical guidance for strategic research prioritization, particularly in identifying high-momentum areas where chemistry innovation and property enhancement converge to address unmet application needs.

3.3 Landscape Analysis of Emerging Polymer Topics Based on CAS Indexed Scientific Concepts

To identify emerging topics within the polymer field, we analyzed CAS indexed concepts from publications containing polymers (see Section 2.1) across both journal articles and patent families from 2020 to 2024. This approach provides quantitative insights into research trajectories and commercial development priorities.

For journal publications, 124,301 unique concepts were extracted, with analysis restricted to those appearing in ≥35 publications. For patent publications, 350,125 concepts were identified, limited to those present in ≥50 patent families. Concepts demonstrating an average annual fold increase of ≥1.75 were classified as high-growth and subsequently categorized into thematic research areas.

3.3.1.Emerging Topics in Journal Publications

Analysis of high-growth concepts in journal publications reveals distinct research priorities shaped by sustainability imperatives and

technological advancement (**Figure 19**). Eight primary thematic areas emerged from the data, each characterized by specific growth patterns and concept clusters.

The highest growth rates were observed in sustainable materials and waste management, where pyrolysis applications demonstrated 4.4-fold growth, indicating strong research focus on chemical recycling and polymer-to-fuel conversion strategies. Lignocellulosic materials (2.5-fold) and chitosan-based synthetic fibers (2.4-fold) further emphasize the shift toward renewable feedstocks and biodegradable alternatives. These growth patterns align with circular economy objectives and represent a fundamental reorientation of polymer research priorities.

Energy storage applications showed differential growth across battery chemistries. Lithium-ion battery concepts grew 4.7-fold while zinc-ion technologies demonstrated 2.9-fold growth, reflecting both the maturation of lithium-based systems and exploration of alternative chemistries. The parallel development of these technologies indicates polymer research addressing multiple energy storage pathways for grid-scale and mobile applications.

Advanced electronics and flexible devices represent another high-growth area, with flexible electric circuits showing 2.0-fold growth and motion sensors demonstrating 2.0-fold growth. These concepts reflect the increasing importance of polymer materials in enabling conformable and stretchable electronic systems for wearable technologies and soft robotics applications. In advanced materials, nanoclays exhibited the highest growth at 4.7-fold, suggesting their emergence as versatile reinforcing agents across multiple polymer systems. Surface treatment innovations, particularly anti-counterfeiting applications (4.4-fold growth), indicate growing intersection between polymer science and security technologies.

Characterization techniques showed significant advancement, with flowability studies (3.7-fold) and mid-IR spectroscopy (3.1-fold) demonstrating increased adoption. This growth in analytical capabilities parallels the increasing complexity of polymer systems being developed.

3.3.2.Emerging Topics in Patent Publications

Patent publication analysis reveals commercially-driven research priorities with notable differences from academic trends (**Figure 20**). The data identifies ten major thematic areas with distinct growth trajectories reflecting industrial R&D focus.

Energy storage systems dominate the high-growth landscape, with zinc-ion secondary batteries showing exceptional 13.6-fold growth, substantially exceeding their journal publication growth rate. This disparity suggests accelerated commercial development of zinc-ion technologies. Membrane electrode assemblies (4.8-fold) and lithium-ion batteries (4.7-fold) maintain consistent growth across both publication types, indicating sustained commercial interest in electrochemical energy storage components.

Sustainable polymer concepts in patents emphasize practical applications, with carbon sequestration (3.9-fold) and construction waste management (3.1-fold) showing strong growth. Lignocellulosic materials (2.6-fold) appear consistently across both publication types, confirming their commercial viability as bio-based feedstocks.

Advanced membrane technologies demonstrate significant commercial interest, with electrodialysis showing 1.8-fold growth and electrodialysis membranes at 4.3-fold growth. Gas-liquid separation concepts (1.8-fold) further indicate the importance of polymer membranes in industrial separation processes. These technologies address critical needs in water treatment, chemical processing, and energy applications.

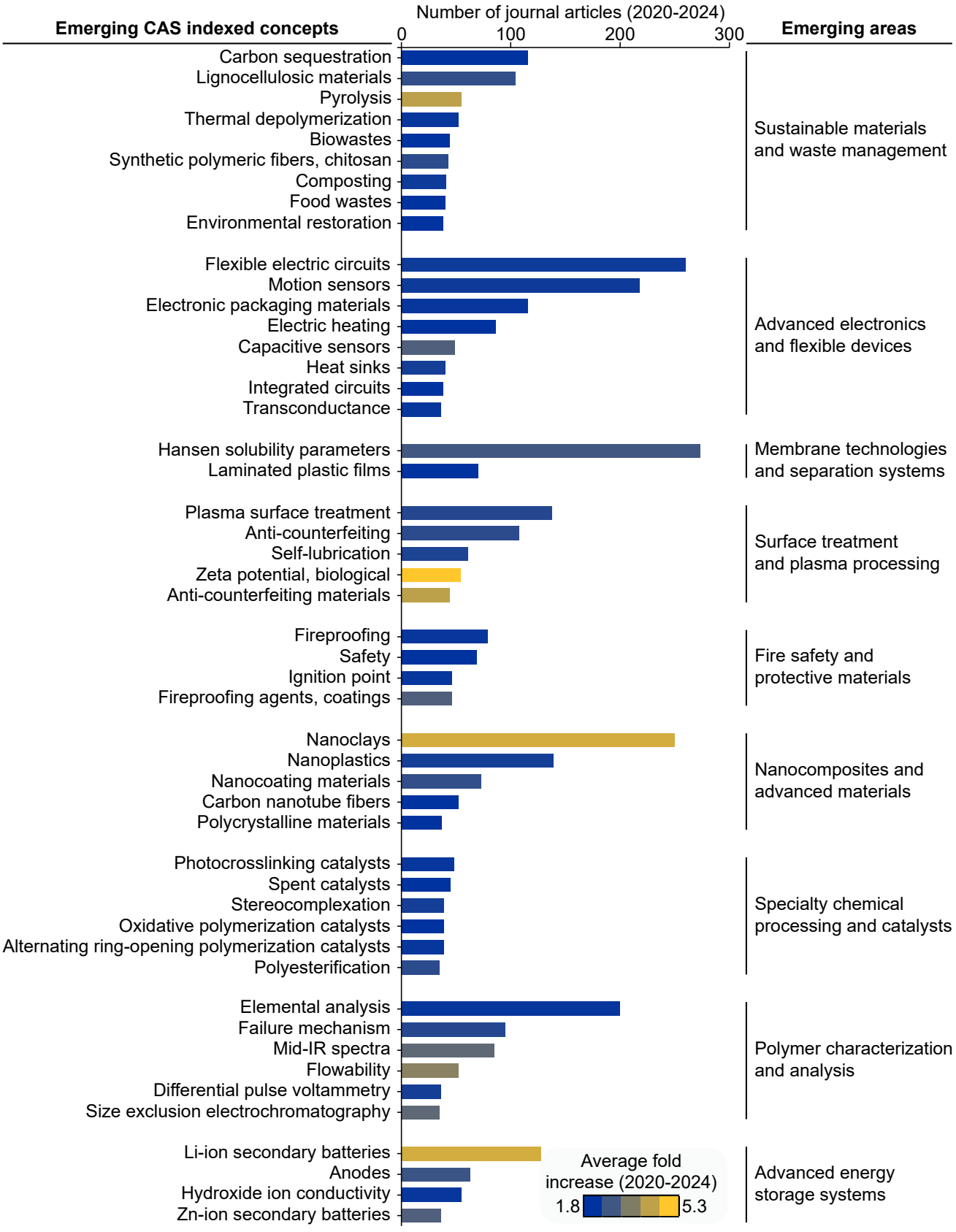


Figure 19. Emerging CAS indexed concepts from journal publications grouped into research areas. The bars are color code according to their average fold increase during the period (2020-2024).

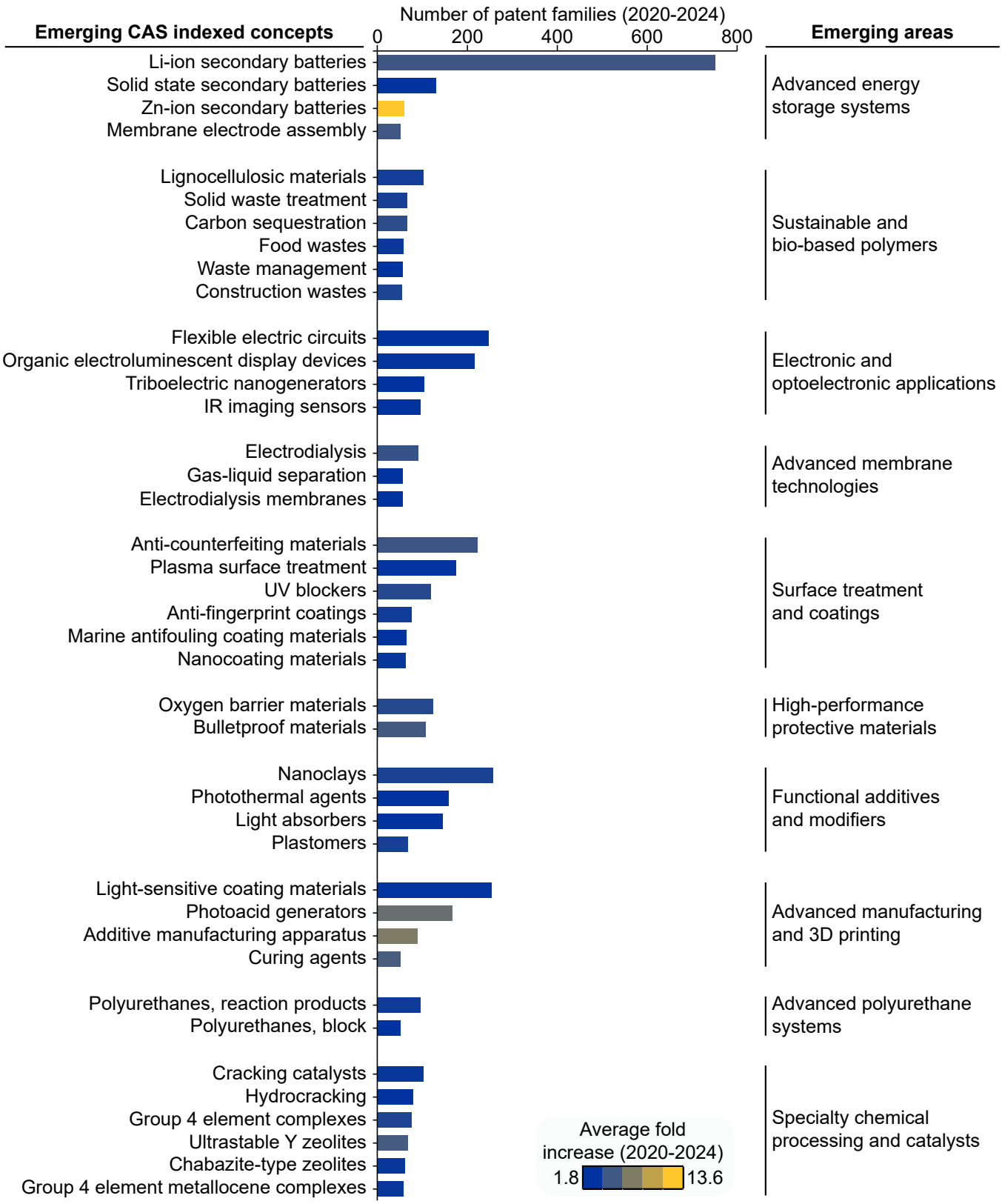


Figure 20. Emerging CAS indexed concepts from patent publications grouped into research areas. The bars are color code according to their average fold increase during the period (2020-2024).

Electronic and optoelectronic applications show diverse growth patterns, with flexible electric circuits demonstrating 1.8-fold growth in patent filings, consistent with their emergence in journal publications. This parallel growth suggests synchronized academic and commercial development of flexible electronics platforms.

Advanced manufacturing demonstrates remarkable patent activity, with additive manufacturing apparatus (7.6-fold) and photoacid generators (6.7-fold) leading growth. This concentration of patents in 3D printing technologies indicates rapid commercialization of polymer-based additive manufacturing systems requiring specialized photopolymerization chemistry.

Surface treatments and coatings show diverse commercial applications, with anti-counterfeiting materials (4.6-fold) and electrodialysis membranes (4.3-fold) representing distinct market segments. High-performance protective materials, including bulletproof systems (5.0-fold growth), indicate defense and security applications driving polymer innovation.

3.3.3.Comparative Analysis and Emerging Subtopics

Comparison of journal and patent landscapes reveals convergent and divergent trends that define emerging polymer subtopics. Energy storage applications show consistent prominence across both domains, with polymer components for batteries representing a mature yet rapidly advancing field. The higher growth rates in patents for zinc-ion systems (13.6-fold vs. 2.9-fold) suggest accelerated technology transfer from research to commercial development.

Sustainability-focused concepts appear prominently in both landscapes but with different emphases. Journal publications prioritize fundamental materials development (lignocellulosic feedstocks, biodegradable polymers), while patents focus on application-specific implementations (carbon sequestration, waste management systems).

Advanced manufacturing and 3D printing emerge primarily through patent activity, indicating industry-led innovation in this domain. The concentration of photopolymerization-related concepts suggests polymers enabling next-generation manufacturing technologies.

The consistent appearance of membrane and separation technologies across multiple concept clusters, from electrodialysis to gas-liquid separation, indicates their emergence as a distinct polymer application area warranting dedicated investigation.

These data-driven insights identify five critical areas where polymer innovation shows sustained momentum: energy storage systems, sustainable and bio-based polymers, electronics and advanced manufacturing, membrane technologies, and emerging polymer architectures representing frontiers in materials discovery.

3.4 Emerging Research Areas in Focus

The comprehensive analysis of NLP-derived emerging topics and CAS indexed concepts across nearly one million polymer publications provides a data-driven foundation for identifying critical areas warranting in-depth investigation. The convergence of patent and journal publication trends reveals distinct thematic clusters that transcend traditional polymer categorizations, highlighting areas where scientific innovation meets pressing technological and societal needs.

Our analysis revealed that energy storage applications emerged as one of the most dynamic sectors across both patent and journal landscapes. The exceptional growth in battery technologies, spanning Li-ion, Zn-ion, and emerging alternative systems, along with membrane electrode assemblies and specialized polymer electrolytes, indicates a field responding to urgent global energy transition demands. This consistent prominence across publication types justified dedicated examination of polymers in energy storage systems, where materials innovation directly impacts electrochemical performance, safety, and sustainability.

The striking emergence of sustainability-focused concepts throughout the dataset, from lignocellulosic feedstocks and chitosan-based materials to pyrolysis applications and carbon sequestration technologies, demonstrates a fundamental shift in polymer science priorities. The parallel growth in waste valorization, construction waste management, and chemical recycling approaches signaled that recyclable, biodegradable, and bio-based polymers represent not merely a research trend but a transformative movement requiring comprehensive analysis.

The convergence of advanced manufacturing concepts with electronic applications revealed flexible electronics as a critical innovation frontier. Our NLP analysis identified strong clustering around flexible electronics, conductive polymers, and specialized processing methods across both patent and journal landscapes, while the simultaneous emergence of multifunctional polymer systems, from conductive materials to substrates and encapsulants, indicated that polymers serve as fundamental enablers in this domain. The robust translation from academic research to commercial patents, coupled with polymers' unique ability to provide mechanical flexibility, processability, and functional tunability essential for bendable and stretchable devices, justified dedicated examination of polymer materials for flexible electronics.

Membrane technologies emerged as a distinct high-growth cluster, with antifouling membranes and electrodialysis applications showing exceptional expansion across both patent and academic literature. The convergence of separation science with polymer engineering, evidenced by increased focus on Hansen solubility parameters and surface modifications, justified dedicated investigation of polymers in membrane and filtration technologies.

Beyond these application-focused areas, our analysis identified multiple emerging polymer architectures and functionalities that represent frontiers in fundamental polymer discovery. The consistent appearance of concepts related to conductive polymers, dynamic networks, hyperbranched architectures, and framework materials across diverse application contexts suggested these represent platform technologies with transformative potential. The growth in specialized polymer classes, from next-generation polyesters addressing sustainability challenges to high-performance elastomers meeting extreme application demands, indicated that materials innovation continues advancing on multiple fronts simultaneously.

This data-driven approach to topic selection ensures our detailed investigations align with genuine research momentum rather than perceived importance, providing strategic insights into areas where polymer science is actively addressing global challenges and creating new technological possibilities.

4. Polymers in Energy Storage Systems: Materials Enabling the Energy Transition

4.1 Technology Context and Overall Trends

NLP analysis of our data revealed emerging usage of polymers in energy-storage–oriented applications in both journals and patents. This rise underscores how polymers are increasingly integrated into energy storage systems to enhance mechanical flexibility, improve ionic and electronic transport, optimize interfacial stability, and support lightweight, scalable device architectures. Their tunability positions polymers as key enablers across multiple energy storage technologies.

To better understand how polymers contribute to this expanding landscape, we categorized energy storage systems into four major segments: batteries, capacitors, thermal energy storage (TES), and chemical energy storage. Within batteries and capacitors, polymers commonly function as electrolytes, binders, separators, active material hosts, and protective interfaces, supporting performance metrics such as cycling stability, conductivity, and safety.[313, 314] In TES, polymer matrices and phase-change polymer systems offer controlled heat storage and release,[315] while in chemical energy storage, functional polymers aid in gas capture, hydrogen storage, and catalytic processes.[316]

We further examined the number of documents related to these energy storage systems in our polymer data and saw their publication growth within journals and patents, as shown in **Figure 21**. The trends align with our NLP analysis, publication activity accelerates notably after 2020, with journals roughly doubling from late-2010s and patents rising even more steeply.

In the patent landscape, battery dominance signals that polymer functions such as ion transport, interfacial stability, safety, and manufacturability are closest to commercialization, underscoring polymers' rising status as critical enablers of next-generation batteries amid demand for flexible, lightweight, safer storage. The journal mix is more diversified, alongside strong growth in batteries, capacitors remain steady contributors and TES expands fastest from ~2021 onward, pointing to active academic exploration of polymer roles in dielectric management, thermal regulation, and encapsulation. Chemical energy storage remains surprisingly underexplored despite polymers' potential in hydrogen storage and other chemical energy storage systems, representing a significant opportunity gap.

The overall trend indicates that the field has transitioned from diverse exploratory research to concentrated efforts in batteries and capacitors, with 2020 marking a clear inflection point where both academic and industrial activities accelerated dramatically, possibly driven by the worldwide push for cleaner energy and the growing adoption of electric vehicles.

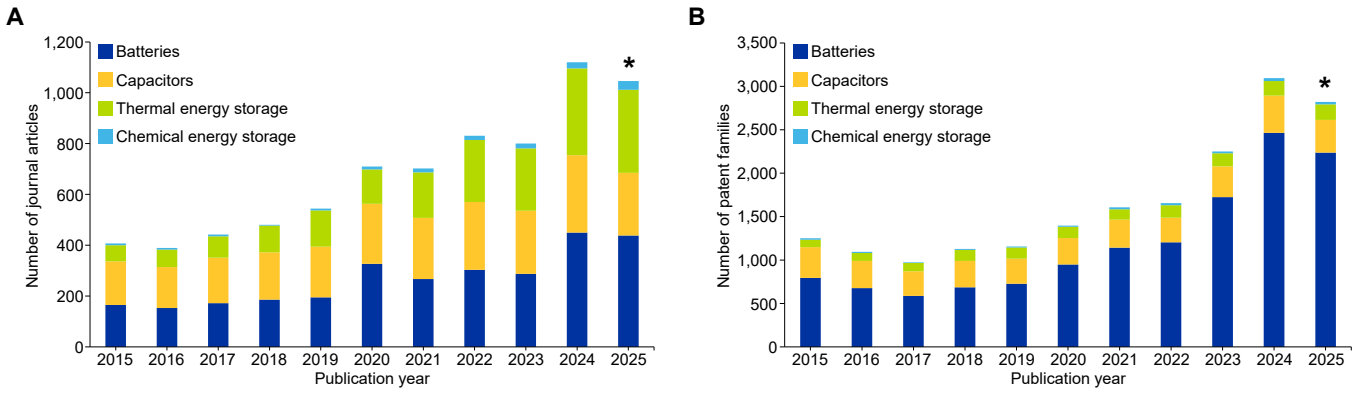


Figure 21. Publication trends of (**A**) journal articles and (**B**) patent families in the field of energy storage systems. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025. *Data only for the months January to November in 2025.

4.2 Polymer Materials Across Energy Storage Systems

We analyzed the various polymers and their classes which are being used across the main energy storage systems. By highlighting where their use is growing and how their roles differ in batteries, capacitors, thermal energy storage, and chemical energy storage, we aim to better understand where innovation is concentrated and how polymer requirements differ across technologies.

To examine how polymers are progressing toward commercialization across different energy storage systems, we analyzed the most widely used and fastest-growing polymer classes from 2020 to 2024 (**Figure 22**). As highlighted earlier in **Figure 21**, the patent landscape is heavily dominated by batteries, and this pattern persists throughout the 2020–2024 period as well (**Figure 22**). Batteries account for an overwhelming 75% of all polymer-related energy storage patents, underscoring their centrality in current innovation efforts. Capacitors follow with 17%, while thermal and chemical energy storage contribute only 7% and 1%, respectively, signaling that these areas remain significantly underdeveloped and may offer substantial room for future growth.

The polymer classes across different energy storage applications reveal distinct material preferences driven by specific performance requirements. In the battery sector, fluoropolymers emerge as the clear leader with exceptional growth rates (shown in deep blue), likely driven by their superior chemical stability and ionic conductivity properties essential for next-generation battery separators and binders.[317] Polyesters and polyoxyalkylenes also show strong patent activity with high growth rates, suggesting their increasing importance in battery components. Notably, styrene-butadiene rubber (SBR) displays remarkable growth momentum, indicating its expanding role beyond traditional applications into advanced battery binders and flexible electrode materials.[318]

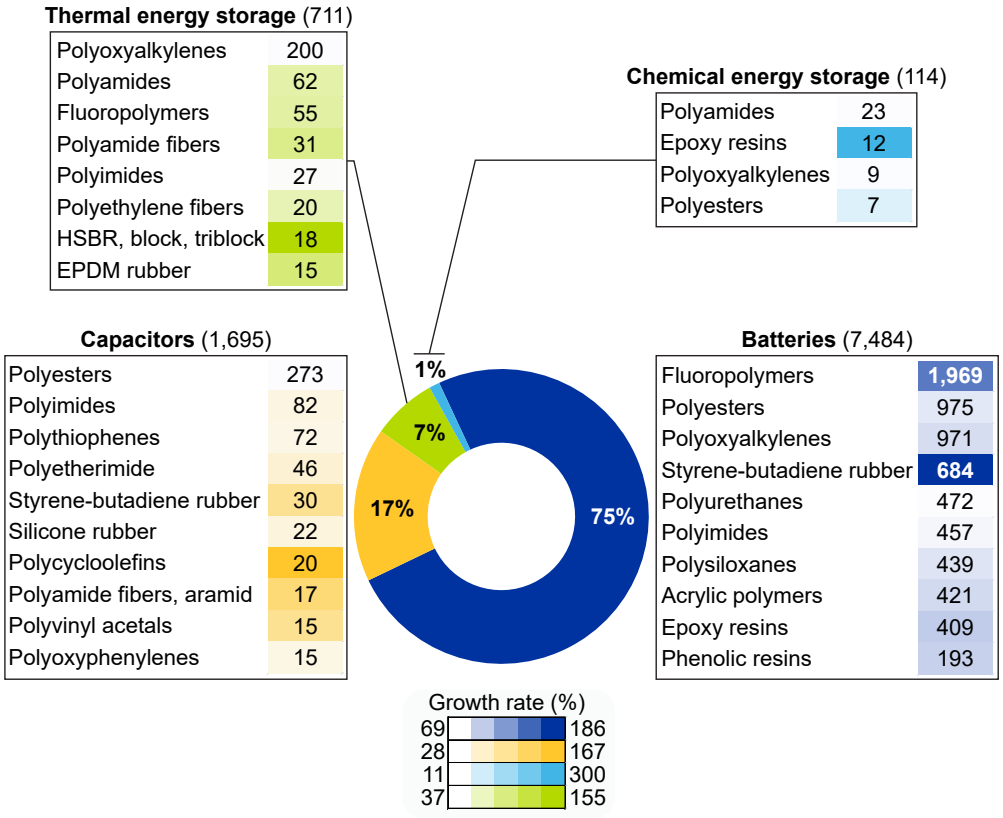


Figure 22. Donut chart represents the distribution of patent families across four major energy storage systems: batteries, capacitors, thermal energy storage, and chemical energy storage. The corresponding heatmaps highlight the emerging polymer classes within each segment, ranked by their volume of patents, with color intensity indicating relative growth rates. Data includes journal and patent publications in the field of polymers for the period 2020-2024 from the CAS Content Collection.

The capacitor segment reveals a dynamic innovation landscape. Polyesters dominate the patent count but display low growth rates, suggesting market saturation in traditional dielectric applications. Polyimides and polythiophenes show moderate patent activity and growth, indicating continued development as the high-performance dielectrics and tunable conductive materials, respectively. Notably, polycycloolefins, SBR, polyamide fibers (aramid), and polyvinyl acetals, have a low patent count but their high growth rate indicates ongoing exploration of lightweight, flexible, high-frequency, and high-temperature capacitor materials.

Thermal energy storage presents an interesting dichotomy. Polyoxyalkylenes lead in patent numbers but show low growth rates, suggesting this is a mature application area, likely as phase change materials (PCMs). Similarly, polyamides and fluoropolymers show substantial patent activity but modest growth. However, smaller volume materials like hydrogenated SBR (HSBR) block copolymers and ethylene propylene diene monomer (EPDM) rubber display higher growth rates and emerging innovations in specialized thermal management applications.

Chemical energy storage remains the smallest segment at just 1% of patents, highlighting a significant innovation gap. Polyamides lead in patent count but with minimal growth, while epoxy resins, despite lower numbers, show high growth rates, possibly driven by new applications in hydrogen storage systems or chemical storage technologies. The limited polymer diversity and low overall activity in this segment represents substantial untapped potential for future polymer innovation in chemical energy storage solutions.

Cross-application polymers such as polyimides, polyamides, and fluoropolymers appearing across multiple categories suggest their versatility and potential for creating synergistic solutions across different energy storage technologies. The overall growth rate patterns indicate a shift from traditional polymer applications toward specialized, high-performance materials tailored for specific energy storage challenges, with the most innovations occurring in battery applications.

4.2.1.Batteries: Electrolytes, Binders, and Advanced Functional Polymers

Given the dominant presence of batteries in both the journal and patent landscapes, this segment warrants a closer examination. Their prominence reflects not only the technological maturity and commercial urgency surrounding battery systems but also the increasing dependence on polymers to meet critical performance, durability, and safety demands. Polymers play critical roles in enabling next-generation battery chemistries by supporting ion transport, stabilizing interfaces, improving mechanical integrity, and enhancing thermal and electrochemical stability.

Exploring batteries in greater depth allows us to identify the polymers driving innovation, understand how their roles and usage patterns are evolving, and assess what these shifts suggest about broader industry priorities. The following section outlines the major players and the key polymer trends that are shaping battery-related advancements within the overall energy-storage landscape.

4.2.1.1.Key Players in the Battery landscape

To evaluate commercialization efforts within the battery domain, we identified the major players based on their patenting activity (**Figure 23**). LG Chem leads with highest number of patents, followed by CATL and Toray Industries. Notably, the top 15 players include both battery manufacturers such as CATL, Samsung SDI, BYD, Zhuhai CosMX Battery and chemical companies like LG chem, Toray Industries, Arkema, Asahi Kasei, Zeon. This data reflects two distinct strategic approaches, battery manufacturers directly investing in polymer innovation for their products, versus traditional chemical companies leveraging their advanced materials and polymer expertise to enter the battery supply chain. Notably, Saudi Aramco's presence signals even petroleum companies are recognizing polymers' strategic importance in energy transition.

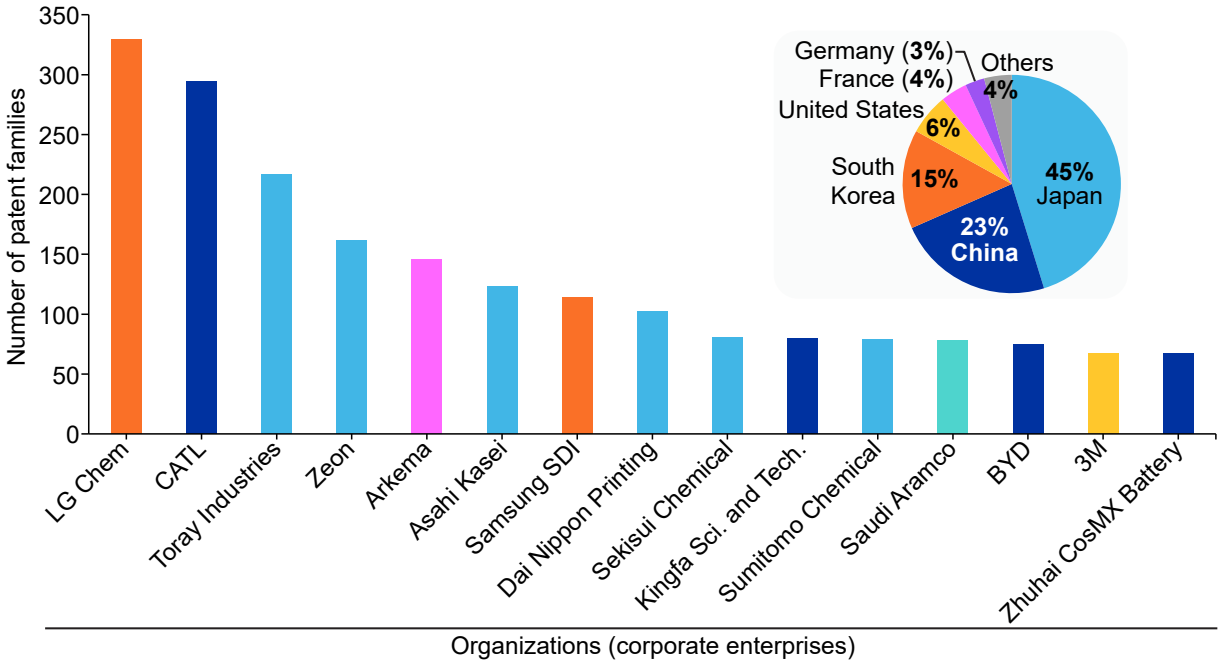


Figure 23. Leading organizations (corporate enterprises) ranked by volume of patent publications related to batteries for the period 2015-2025. The inset pie chart shows the volume of patents published by countries/regions in this field.

The geographic distribution of top corporate patent assignees in polymer related battery technologies is heavily concentrated in East Asia. Japan holds the largest share at 45%, led by Toray Industries, Zeon, and Asahi Kasei, reflecting its long term investment in polymer materials and strong ties to the automotive and electronics sectors. China accounts for 23%, driven by major battery manufacturers such as CATL, BYD, Kingfa, and Zhuhai CosMX Battery, while South Korea contributes 15% through LG Chem and Samsung SDI. Western representation remains limited, with the United States at 6%, France at 4%, Germany at 3%, and additional contributions from Saudi Aramco and other countries (4%). Together, East Asian companies represent 83% of the leading commercial assignees, underscoring the region's dominant position in polymer enabled battery innovation. This geographic imbalance indicates that Western companies may be falling behind in polymer-based battery innovation or pursuing alternative technological pathways, while Asia consolidates its leadership in next-generation energy storage materials.

4.2.1.2.Emerging Polymers and Their Classes in Lithium-Ion Batteries

LIBs are already a well-established and commercially mature technology, making it essential to focus on where industry investment is actively driving material innovation. In this context, patents offer a more accurate reflection of the polymer classes that companies consider critical for real-world deployment, compared with the broader and more exploratory nature of academic research. By examining the patent landscape for LIBs, we gain a clearer understanding of which polymer families are being adopted at scale, how their roles are evolving, and how they contribute to the competitive positioning of major players. This section presents these patent-derived insights to illustrate how polymer innovation is progressing within LIB systems.

We identified the most widely used polymer classes and the key polymers within each group, while also highlighting those with the fastest growth in patent activity, as shown in **Figure 24**. This analysis offers a clear view of which polymers the industry is prioritizing and where commercial

development efforts are currently shifting. Our study examined major polymer classes, each displaying different levels of adoption and growth momentum in the LIB landscape. Polyolefins constitute the largest share of patent filings, followed by fluoropolymers, natural polymers, and polyethers. The remaining significant categories include acrylic polymers, synthetic rubbers, vinyl polymers, and polyesters.

Within the polyolefin class, PE and polypropylene (PP) lead with exceptionally high patent counts and faster growth in the recent years, underscoring their continued importance in battery separators, where low cost, chemical stability, and mechanical robustness are essential.[319, 320] These polymers are easy to form into uniform porous membranes that allow lithium-ion flow while preventing short circuits. Moreover, isotactic PP demonstrates strong growth momentum even though having less document count. Isotactic PP is probably gaining attention due to its highly ordered molecular structure which gives it higher crystallinity, translating to greater mechanical strength, better thermal resistance, and more uniform pore formation, making it a next-generation material for high-performance LIBs.[321]

Fluoropolymers are similarly strong, driven by materials widely used in electrode binders and separator coatings. The consistently high

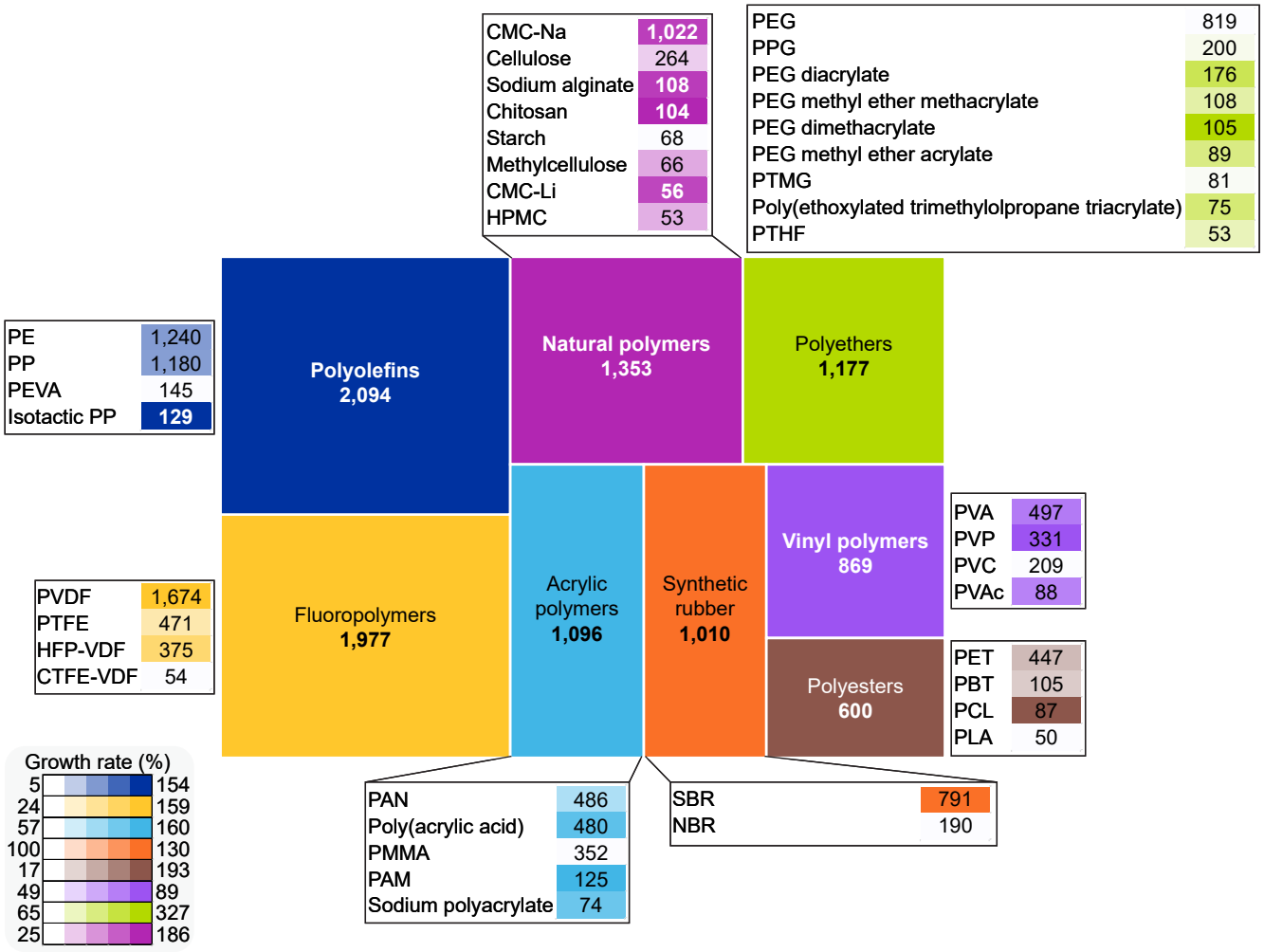


Figure 24. Distribution of patent families across various polymer classes utilized in lithium-ion batteries in the polymers dataset shown as a treemap. The corresponding heatmap tables highlight the emerging polymers within each class, ranked by their volume of patents, with color intensity indicating relative growth rates for the period 2020-2024. Data includes patent families in the field of polymers for the period 2015-2025 from the CAS Content Collection.

patent activity reflects industry reliance on their electrochemical stability, chemical resistance, thermal and mechanical robustness and strong adhesion properties, key for cycle life and safety.[322] They also form robust, uniform films that help maintain electrode integrity during repeated charge–discharge cycles. The fluoropolymer category is led by PVDF, exhibiting high growth rate as well as high patent count, followed by polytetrafluoroethylene (PTFE) and hexafluoropropylene-vinylidene fluoride copolymer (HFP-VDF) maintaining steady growth. Where PVDF and PTFE are generally used as the electrode binders,[323, 324] HFP-VDF is commonly used in gel polymer electrolytes and separator coatings, making them useful for the next-generation LIBs.[325]

Natural polymers present an interesting dichotomy between established and emerging materials. Sodium carboxymethyl cellulose (CMC-Na) leads with highest number of patents and high growth, while other polysaccharides like sodium alginate, and chitosan, show lower patent volumes but similar moderate growth patterns. This aligns with industry trends toward water-processed, cost-efficient, and environmentally safer binder systems, especially for high-capacity anodes.[326] Their ability to be processed in water, rather than toxic organic solvents, significantly reduces manufacturing cost and environmental impact. Other cellulose derivatives such as lithium carboxymethyl cellulose (CMC-Li) also shows faster growth, probably because replacing sodium (Na^+) with lithium (Li^+) in the polymer backbone enhances electrochemical compatibility and improves performance.[327] Li^+ interacts more effectively with active materials, lowering interfacial resistance and enhancing ionic transport.[328] This often leads to improved cycle stability, lower impedance, and better rate capability compared with traditional CMC-Na, explaining its growing adoption in next-generation LIB research and patents.

Polyethers remain important due to their roles in gel polymer electrolytes, ion-conducting matrices, and interfacial engineering.[329] Polyethylene glycol (PEG) remains the most widely patented, because it provides a unique combination of ion-transport capability, flexibility, and compatibility with battery electrolytes, making it valuable in both solid and gel electrolyte systems as well as in binder and coating applications.[330, 331] Moreover, several PEG derivatives such as PEG diacrylate, PEG dimethacrylate, and modified methacrylate variants show high growth rate, suggesting an emerging focus on crosslinked, mechanically reinforced, and tunable polymer networks aimed at improving conductivity and stability in advanced electrolyte formulations for advanced LIBs.[121]

Among synthetic materials, acrylic polymers show high patenting activity because they offer strong binding ability, mechanical stability, and electrolyte compatibility, making them valuable as binders, separators, and components of advanced electrolyte systems.[121] Specifically, polyacrylonitrile (PAN) and poly(acrylic acid) maintain substantial patent portfolios with strong growth. Where PAN is widely used as a precursor for solid polymer electrolytes and as a separator coating due to its exceptional chemical and thermal stability,[332] poly(acrylic acid) is widely used as a water-based anode binder, especially for silicon-rich and other high-expansion materials.[333] Because poly(acrylic acid) is water-processable, it supports more sustainable manufacturing by eliminating toxic solvents. The other emerging polymers are polyacrylamide (PAM) and sodium polyacrylate. They are probably emerging because of their superior binding strength, chemical functionality, mechanical behavior, and environmental advantages, making them strong candidates as binders for next-generation battery electrodes, especially silicon-rich anodes.[334]

Synthetic rubbers are used in LIBs because they provide flexibility, strong adhesion, elasticity, and water-based processing compatibility, making them especially valuable as binders for anodes and as components in flexible or high-durability electrode formulations.[335] In the LIB landscape, this category exhibits particularly strong growth dynamics, with styrene-butadiene rubber (SBR) is highly patented with highest growth rate, highlighting its role as a water-based binder for anodes.[318] Other polymer acrylonitrile-butadiene

rubber (NBR) is emerging probably due to its superior mechanical integrity and chemical robustness, which help in maintaining structural stability and prolonged cycle life, making it suitable for more demanding electrode environments, including silicon-containing anodes that undergo large volume expansion.[336]

Vinyl polymers are gaining importance in LIBs because of their molecular structures which enable unique interfacial, electrochemical, and structural functionalities that differ from other binder classes. In this class PVA and poly(vinylpyrrolidone) (PVP) are leading with steady growth rate, suggesting their continued use in separator coatings, gel polymer electrolytes, and electrode binders.[337, 338] Another emerging vinyl polymer is poly(vinyl acetate) (PVAc) with high growth and low patent count. PVAc is gaining attention as a promising binder due to its balanced mechanical, chemical, and processing advantages, which align with the industry's shift toward sustainable and high-performance electrode materials.[339]

Polyesters, although smaller in overall numbers, have inherently higher polarity and better thermal form stability, which makes them particularly useful for separator technologies and mechanically resilient components in the LIBs. Amongst polyesters, polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) leads, with high patent numbers and moderate growth rate, implying their continued use in separator substrates and thermal-stabilized separators.[340, 341] Moreover, polycaprolactone (PCL) is attracting attention with highest growth rate due to its excellent lithium-ion solvation ability, high flexibility, tunable crystallinity, and compatibility with solid-state and gel electrolyte architectures, aligning with the industry shift toward advanced electrolytes and mechanically adaptive electrode designs.[342, 343]

Overall analysis demonstrates that, while LIB material selection remains anchored by mature polymer families such as polyolefins and fluoropolymers, the strongest growth is concentrated in natural polymers, modified polyethers, and advanced binder systems (acrylic polymers, synthetic rubbers). These trends reflect industry's shift toward improving electrode integrity under high-capacity loading, enabling safer and more sustainable manufacturing, and preparing for next generation LIB chemistries requiring new interfacial and mechanical characteristics. This patent-based view provides a direct window into where companies are prioritizing material innovation and how polymer roles are evolving in commercial LIBs.

4.2.1.3.Polymers and Their Classes in Next-Generation Batteries

As we move beyond lithium-ion, our polymer dataset shows a clear broadening and recent acceleration across next-generation chemistries which include—solid-state, sodium-ion, flow, zinc-ion, and metal–air. **Figure 25** displays the

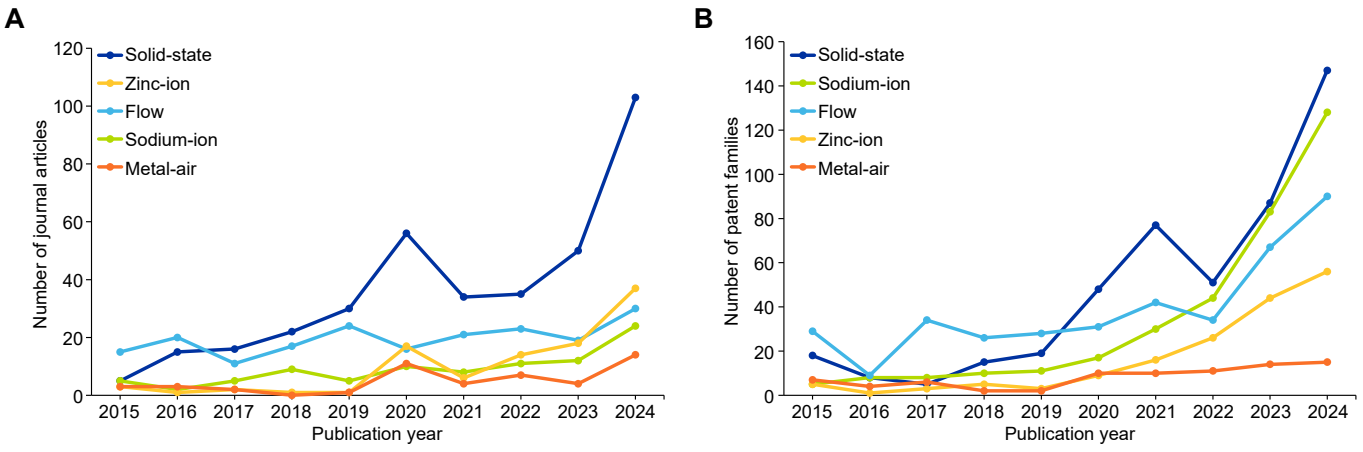


Figure 25. Publication trends in (**A**) journal articles and (**B**) patent families for next-generation battery technologies in the field of polymers for the period 2015-2024 from the CAS Content Collection.

publication trends for these advanced battery chemistries, revealing a fascinating divergence between academic research and commercial development. In journal publications, solid-state batteries have emerged as the clear academic favorite, showing accelerating growth, with a notable spike in 2020 that likely reflects breakthrough discoveries in polymer electrolytes. In contrast, the patent landscape tells a more diversified story of commercialization, where multiple technologies, solid-state, sodium-ion, and flow batteries, all demonstrate sharp upward trajectories from 2021 onwards, reaching comparable levels by 2024.

This divergence between academic and patent activities suggests different maturation stages and commercial viability assessments. The earlier and more volatile academic interest in solid-state batteries, followed by a lag in patent filing, indicates the typical progression from fundamental research to applied development. Meanwhile, the simultaneous patent surge across multiple technologies after 2021 reflects industry's hedging strategy—recognizing that different battery chemistries may serve distinct market segments. Sodium-ion batteries' remarkable patent growth despite modest journal presence suggests rapid commercialization of established science, driven by cost advantages and material abundance. Similarly, flow batteries' stronger patent than publication growth indicates their perceived commercial potential for grid-scale storage despite fewer scientific breakthroughs. The polymer requirements for these diverse systems from solid electrolytes for solid-state batteries to selective membranes for flow batteries are driving specialized polymer development tailored to each technology's unique demands.

To gain deeper insight, we reviewed journal publications and patents to identify the polymers used in these advanced battery chemistries. **Figure 26** reveals distinct polymer utilization patterns across next-generation battery technologies, with notable divergences between academic research and commercial development. Research outputs span a wider chemical palette, whereas patents cluster around materials that are already manufacturable at scale. In other words, journals emphasize discovering interfacial chemistries and transport mechanisms, while patents concentrate on separator substrates, binders, and membrane matrices that fit existing coating lines and supply chains. Notably, few polymers such as PVDF, HFP-VDF, PTFE, PEG, PAN, poly(methyl methacrylate) (PMMA), CMC-Na, PVA, PVP, which appear on both sides, suggest that these polymers are closest to deployment. Other polymers which appear in academic literature only, like poly(oxy-p-phenyleneoxy-p-phenylenecarbonyl-p-phenylene) (PEEK-HT), Bisphenol A polysulfone, poly(m-phenylenebisbenzimidazole) (m-PBI), polydopamine (PDA), cross-linkable PEGs, which are promising but still maturing in cost, processing, or reliability.

Solid-state batteries show the most striking contrast between research and commercialization approaches. Journal articles concentrate heavily on PEG and its cross-linkable derivatives, reflecting academic focus on optimizing ionic conductivity through PEG-based solid polymer electrolytes.[344, 345] The presence of PEG diacrylate and PEG methacrylate derivatives highlights research efforts to balance ionic conductivity and mechanical integrity through network formation. Patents, however, prioritize fluoropolymers, like PVDF, PTFE, and HFP-VDF, alongside diverse materials including polyolefins and SBR, indicating industry's emphasis on electrochemical stability, mechanical robustness, processability, and cost-effective manufacturing, making them suitable as binders, composite electrolyte matrices, and electrode coatings in high-voltage solid-state architectures.[346, 347]

Sodium-ion batteries reveal interesting polymer selection strategies. Journal articles focus more on PEG and selected fluoropolymers, reflecting ongoing investigation into Na^+ transport behavior, electrolyte compatibility, and interfacial chemistry.[348-350] Patents, in contrast, show a strong emphasis on practical electrode and separator materials. PVDF stands out as the most heavily patented polymer, followed by PTFE, polyolefins (PE, PP), and CMC-Na.

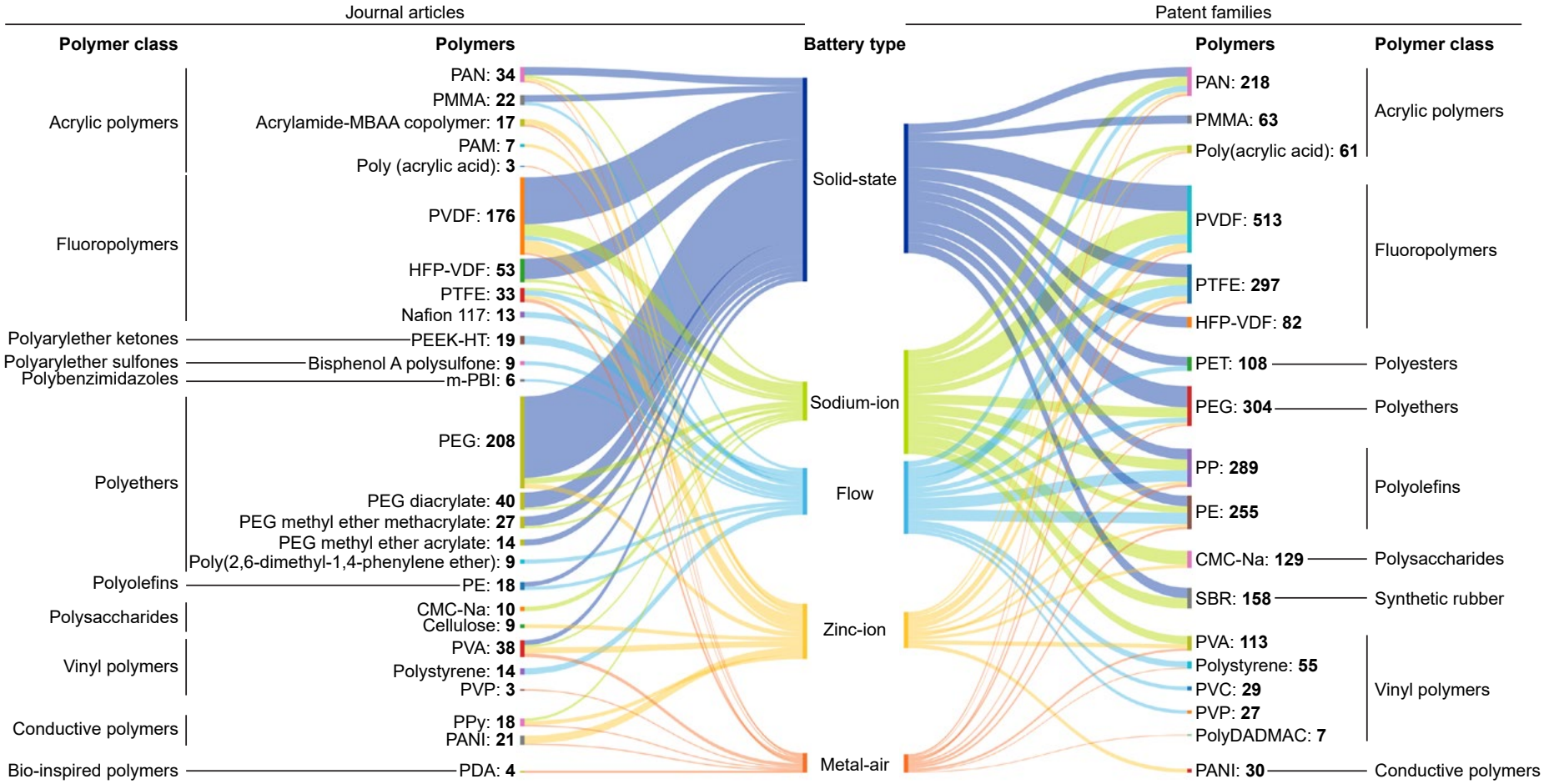


Figure 26. Distribution of polymers and their classes in journal articles (left) and patent families (right) used across next-generation batteries in the polymers dataset for the period 2015-2025 from the CAS Content Collection. Width of each node is directly proportional to the volume of publications.

This combination reflects the industrial need for cost-efficient, chemically stable binders and separator substrates that integrate smoothly into existing manufacturing infrastructure.[351, 352] Moreover, the presence of SBR exclusively in patents indicates industry focus on electrode flexibility and manufacturing scalability.

Flow batteries demonstrate the most distinct academic-commercial divide. Academic research explores specialized high-performance polymers like PEEK-HT, bishphenol A polysulfone, m-PBI and Nafion 117, which are known for their chemical resilience, oxidative stability, and dimensional control in harsh aqueous or non-aqueous redox environments.[353] Their exclusive presence in journals suggests these materials are under active investigation for ion-selective membranes, where long-term chemical durability is critical, but cost and processability remain barriers to commercialization.[354] Patents, conversely, are concentrated on PTFE, PVDF, PEG, PET, and polyolefins (PP and PE), underscoring an industrial preference for chemically inert, scalable, cost-effective alternatives despite potentially lower performance.[355, 356]

Zinc-ion batteries show interesting convergence patterns. Both academic and commercial sectors utilize PVDF extensively, recognizing its value as separator and binder material.[357,358] Conducting polymers like polyaniline (PANI) appear prominently in both journals and patents, reflecting proven zinc-ion storage capability.[359] Patents emphasize sodium carboxymethyl cellulose for practical electrode applications, while journals explore pure cellulose, indicating different approaches to sustainable binder materials.

Metal-air batteries represent the least developed category with minimal polymer diversity. The overall pattern reveals academic research prioritizing performance optimization through specialized polymers, while patent activities reflect industry's pragmatic balance between functionality, scalability, and commercial viability.

The overall analysis of polymer utilization across next-generation battery technologies reveals a clear stratification of technological maturity and commercialization strategies. The overall pattern reveals that academic research explores novel, high-performance polymers optimized for specific electrochemical functions, while patent activities reflect industry's practical approach balancing performance with manufacturing feasibility, cost, and scalability. As these technologies mature, successful commercialization will likely depend on identifying optimal compromises between these competing demands, with polymers serving as the critical enabler for translating laboratory breakthroughs into market-ready energy storage solutions.

4.2.2.Capacitors: Dielectric Polymers and High-Performance Architectures

Another key energy-storage system emerging from our polymer dataset is capacitors. While capacitors differ fundamentally from batteries in their charge-storage mechanisms, they place equally demanding requirements on polymer materials, particularly in terms of dielectric performance, thermal stability, and processability. A fast-growing polymer-enabled research and patent activity in this area reflects sustained efforts to enhance energy density, reliability, and form-factor flexibility across conventional capacitors and advanced supercapacitor systems.

Given their distinct functional requirements and application domains, capacitors offer a unique perspective on how polymer roles diversify across energy-storage technologies. The following section explores the major players and the key polymer trends that are shaping capacitor-related developments, with a focus on identifying areas of the most active material innovation.

4.2.2.1.Key Players in the Capacitor Domain

To evaluate the commercialization efforts in the capacitor field, we identified the top 15 companies based on their patenting activity (**Figure 27**). The patent landscape in this space reveals a highly concentrated market dominated by a single leader and strong geographic clustering. Toray Industries holds a commanding position, nearly triple the patents of its nearest competitors. The second

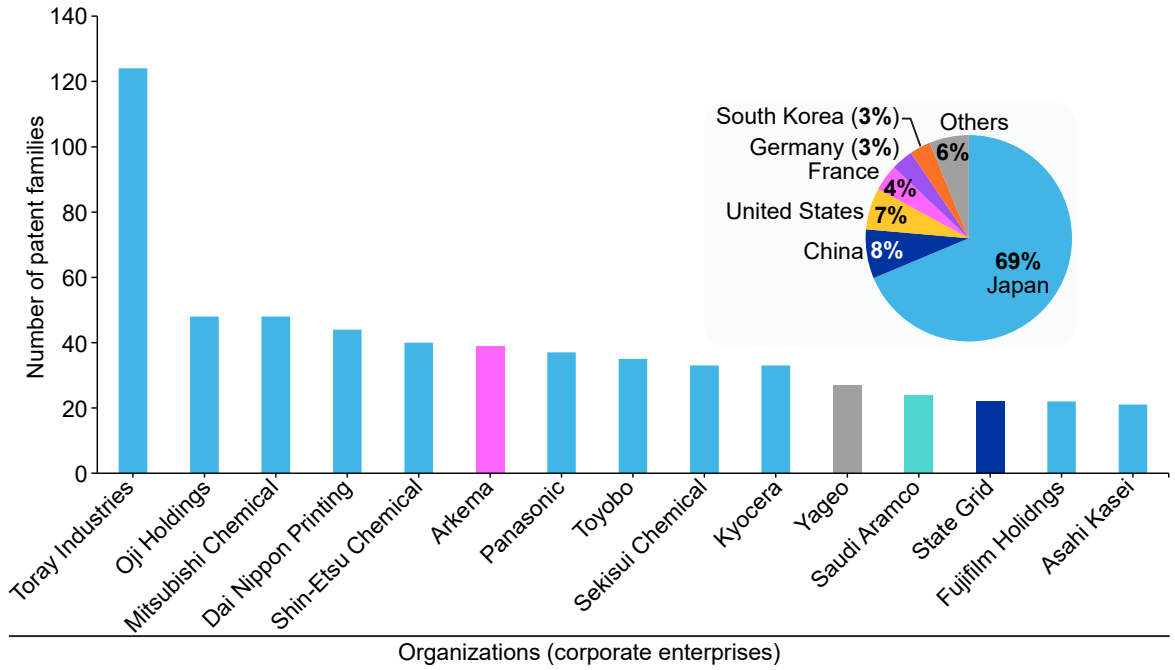


Figure 27. Leading organizations (corporate enterprises) ranked by volume of patent publications related to capacitors for the period 2015-2025. The inset pie chart shows the volume of patents published by countries/regions in this field.

tier comprises several Japanese chemical and materials companies like Oji Holdings, Mitsubishi Chemical, Dai Nippon Printing, and Shin-etsu Chemical. This substantial gap suggests Toray's strategic commitment to polymer-based capacitor technologies, potentially driven by their expertise in high-performance polymer films for dielectric applications. Notably, the presence of non-traditional capacitor companies such as Saudi Aramco and State Grid indicates growing recognition of polymer capacitors' strategic importance across diverse industries. Overall, the patent landscape skews towards companies with deep expertise in polymer films, coatings, and precision processing, with a smaller presence from electronics manufacturers and energy majors. This trend suggests that polymer innovation in capacitors is primarily driven by materials expertise rather than device manufacturing capabilities.

The geographic distribution presents an overwhelming Japanese dominance at 69%, reflecting the country's long-standing leadership in advanced materials and precision manufacturing. China's modest 8% share, despite its manufacturing prowess, suggests the country is still developing capabilities in specialized capacitor polymers. The United States accounts for only 7%, while European presence is limited to France (4%) and Germany (3%), with South Korea surprisingly underrepresented at 3% given its strong electronics industry. This geographic imbalance indicates that polymer innovation for capacitors remains highly specialized, concentrated in countries with established expertise in high-performance polymer films and dielectric materials, particularly Japan's integrated chemical-electronics industrial ecosystem.

4.2.2.2.Polymers and Their Classes in Capacitors

We further identified the polymers and their classes in capacitors domain (**Figure 28**). The polymer distribution for capacitors reveals distinct research and commercialization strategies between academic and industrial sectors. Academic literature focuses on exploratory materials that push dielectric properties and electrochemical performance, whereas industries emphasize polymers that are manufacturable at scale, reliable over

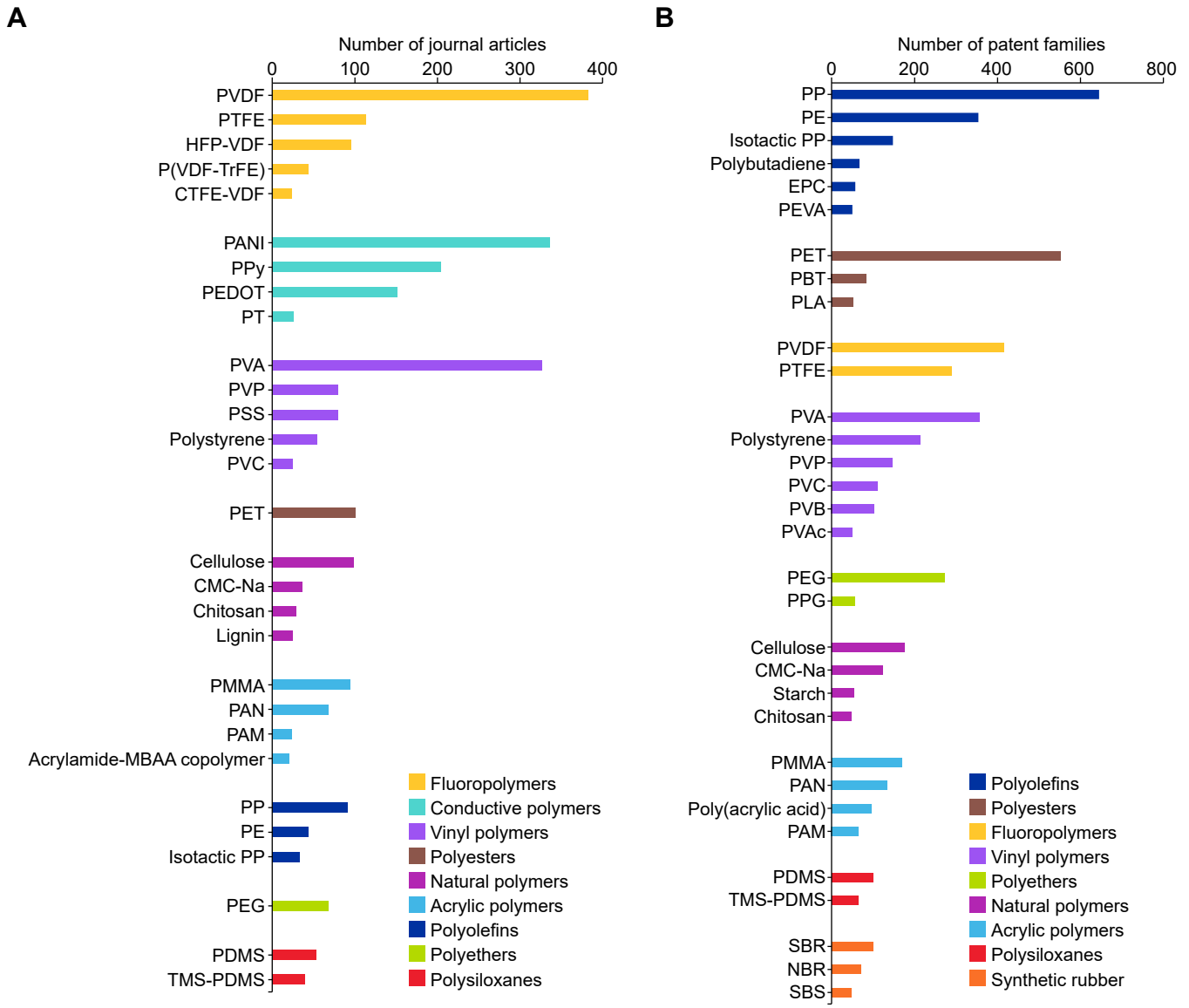


Figure 28. Distribution of polymers in (**A**) journal articles and (**B**) patent families, categorized by polymer class used in capacitors in the polymers dataset for the period 2015-2025 from the CAS Content Collection.

lifetime, and already integrated into film or device production lines. Overall, the data shows a field anchored by established film dielectrics and binders in patents, with journals probing higher-risk, higher-property spaces (e.g., ferroelectric and conducting polymers, bio-derived matrices).

Fluoropolymers demonstrate strong presence in both domains but with different emphases. Journal articles weigh heavily toward PVDF and its variants e.g., HFP-VDF, poly(vinylidene-trifluoroethylene) (PVDF-TrFE), poly(vinylidene fluoride-chlorotrifluoroethylene) (CTFE-VDF), as well as PTFE, reflecting interest in high-ferroelectric behavior, electroactive response, chemical/thermal stability, and roles in gel or solid electrolytes for electrochemical capacitors.[360-362] Patents also show substantial activity for PVDF and PTFE, pointing to binder and coating uses, high-temperature film dielectrics, and surface modification layers, suggesting these materials are used for high-performance capacitors.[363] Overall, academia is exploring property amplification, while industry is protecting integration and reliability.

Polyolefins present the most dramatic academic-commercial divergence. While journal representation is modest, patents show overwhelming dominance with PP leading all polymers. This inverse relationship indicates polyolefins have transcended the research phase, becoming the industrial workhorses for capacitor dielectrics due to their excellent processability, low cost, and reliable performance in biaxially-oriented film form.[364, 365]

Conducting polymers exhibit the opposite pattern, with substantial academic presence from PANI, polypyrrole (PPy) and poly(3,4-ethylenedioxythiophene) (PEDOT) but virtually no patent activity. This stark contrast highlights the persistent challenge of translating these materials' impressive laboratory performance in electrochemical capacitors into commercially viable products, hampered by stability, and processability.[366] Meanwhile, polyesters show strong commercial adoption with PET dominating, reflecting its established role in film capacitors.[367] The patent landscape includes additional polyesters such as PBT, PLA, which are absent from academic literature, indicating industrial optimization of existing platforms rather than fundamental research.

Vinyl polymers and polyethers bridge processing and performance. PVA is conspicuous in both panels, in journals, it reflects the popularity of PVA-based hydrogels and gel electrolytes[368] and in patents, it indicates film-forming, binders, and membrane roles that are straightforward to scale.[369] PVP, polystyrene, poly(vinyl chloride) (PVC), poly(vinyl butyral), and PVAc appear more strongly in patents than in journals, pointing to adhesion layers, interlayers, and lamination chemistries that improve film handling and metallization reliability.[370, 371] In addition, journals also focus on specialty materials like poly(styrenesulfonic acid) (PSS) for its ionic conductivity. However, polyethers like PEG, and polypropylene glycol (PPG) are more prominent in patents than in journals, consistent with their use as electrolytes, polymer matrices, binders, and dielectric modifiers, indicating their transition to commercialization in electrolytic capacitors and supercapacitors.[372, 373]

Natural and acrylic polymers signal a push toward greener processing and mechanical control. Cellulose and CMC-Na appear in both panels, with a tilt toward patents, reflecting their roles in separators, aqueous binders, and porosity control, attractive for cost and sustainability.[374, 375] Among acrylics, PMMA, PAN, poly(acrylic acid), and PAM show strong patent presence, aligned with dielectric coatings, pore-formers, separator supports, and adhesion control.[376] Their journal visibility is steady but lower, suggesting that the major advances are in formulation and processing research rather than in discovering entirely new acrylic chemistries.

Polysiloxanes and synthetic rubbers fill niche but important roles. Poly(dimethylsiloxane) (PDMS) and trimethylsilyl-terminated poly(dimethylsiloxane) (TMS-PDMS) appear across both panels, associated with flexible/stretchable dielectrics, and encapsulants, where chemical stability and elasticity are needed.[377,378] Elastomeric binders like SBR, NBR, styrene-butadiene-styrene copolymer (SBS) are more visible in patents, indicating manufacturable solutions for flexible environments, and pointing to device-integration IP rather than material discovery.[379, 380]

This comprehensive analysis reveals that capacitor polymer development follows distinct trajectories, academic research explores performance frontiers, while industry optimizes cost-effective, manufacturable solutions.

4.2.3.Thermal Energy Storage: Polymer-Based Phase Change and Insulation Materials

Moving ahead, TES emerges as another important class of energy storage systems identified within our polymer dataset. Unlike batteries and capacitors, which primarily store energy in electrical or chemical forms, TES systems operate by capturing and retaining heat energy for later use. Polymers play a critical role in this domain due to their tunable thermal properties, processability, design flexibility, chemical versatility, low density, and compatibility with diverse thermal storage mechanisms.

Polymers are widely explored as active storage media, phase-change materials, supporting matrices, encapsulation layers, and active components in TES systems, enabling both sensible and latent heat storage. The following section examines these key polymer trends, which are shaping the future trajectory of TES, highlighting material systems where innovation is accelerating and new opportunities are emerging.

4.2.3.1.Polymers and Their Classes in TES

We examined the key polymers and their corresponding classes within the TES domain, as summarized in **Figure 29**. The polymer landscape for TES reveals distinct patterns in material selection between academic research and commercial development, reflecting differing priorities in the design of PCMs and associated encapsulation strategies. Journal articles capture areas where the research community is actively exploring and engineering new material concepts, whereas patent filings highlight where industry is focusing on scalable, manufacturable, and application-ready formulations. Although there is clear overlap between the two landscapes, each prioritizes different polymer families for different reasons, academic studies

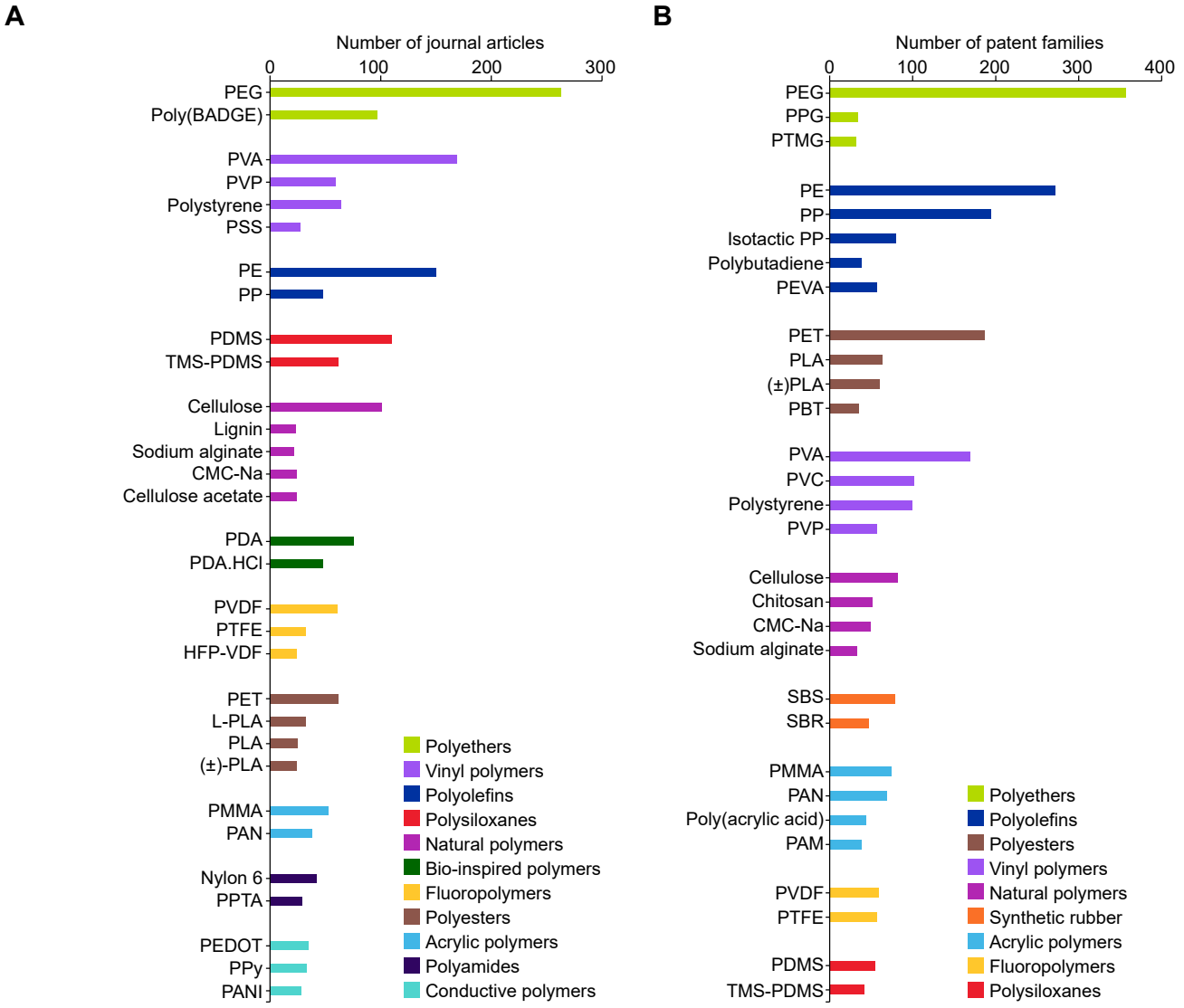


Figure 29. Distribution of polymers in (**A**) journal articles and (**B**) patent families, categorized by polymer class used in thermal energy storage systems in the polymers dataset for the period 2015-2025 from the CAS Content Collection.

emphasize novel architectures, mechanisms, and multifunctional behavior, while patents favor robust material platforms that can be processed at large scale and readily integrated into practical TES products.

Polyethers dominate both journals and patents, with PEG standing out as the most frequently appearing polymer by a wide margin. This observation is expected in TES applications, as PEG is widely recognized as a practical polymeric PCM.[381] PEG stores thermal energy predominantly through latent heat associated with reversible melting and crystallization, and its phase transition temperature can be systematically tuned through controlled variation of molecular weight and formulation.[382] Moreover, its strong presence in both journal publications and patents reflects its key advantages, including ease of processing, high latent heat storage capacity, excellent chemical stability, and broad compatibility with common encapsulation methods and composite manufacturing strategies.[383, 384]

Polyolefins show the second strongest presence, with a pronounced divergence between academic and commercial emphasis. While journals report moderate activity, patents exhibit substantial representation, indicating that much of industrial TES innovation is focused on composite engineering approaches.[385] In these systems, low-cost and highly processable matrices such as PE and PP are used to encapsulate and stabilize PCMs while addressing practical challenges including leakage control, mechanical integrity, thermal cycling durability, and scalable manufacturing.[386, 387] Their chemical inertness, low cost, and excellent processability position polyolefins as preferred materials for large-scale TES applications.

Vinyl polymers show strong representation in both journals and patents, with PVA emerging as a dominant material in each. PVA is widely used in TES due to its excellent binding ability, film-forming nature, and capacity to form interconnected polymer networks, making it well suited as a supporting matrix for composite PCMs and as a functional encapsulation component.[388, 389] Patents also display significant activity around PVC and polystyrene, which are commonly employed as rigid matrices in microencapsulation and composite TES structures due to their thermal and mechanical stability under repeated cycling.[390, 391] PVP appears in both domains with moderate presence, valued primarily as a dispersant and stabilizer that mitigates phase separation and enhances thermal cycling reliability.[392]

Polyesters, particularly PET and PLA stereoisomers, show stronger presence in patents. PET is a widely used structural and barrier polymer in films, fibers, and packaging-like formats, which align naturally with TES product implementations such as encapsulated PCMs, stable composites, and thermoregulating textiles.[393, 394] PLA's appearance often reflects industrial push toward bio-based and sustainability-forward TES components. Moreover, acrylic polymers represent another class which is present in both panels. These polymers are important for TES because they act as supporting matrix materials for PCMs, providing high mechanical strength, thermal stability, and form-stable storage.[395, 396] PMMA is a well-established encapsulation polymer, and PAN offers a robust matrix for PCM composites, driving strong industrial interest in acrylic-based microencapsulation and composite strategies.[397,398]

Polysiloxanes (PDMS and modified PDMS such as TMS-PDMS) appear in both panels, indicating their specialized role as thermally conductive matrices and flexible encapsulation materials that maintain performance across wide temperature ranges.[399, 400] Moreover, **Figure 29** also shows that natural polymers, notably cellulose, sodium alginate and CMC-Na represent a growing segment in both journals and patents. These polymers are frequently used as porous scaffolds, aerogels, fibers, or network matrices that physically confine PCMs and reduce leakage.[401, 402] This pattern also suggests commercial interest in sustainable, biodegradable encapsulation materials and bio-based PCM composites, moving beyond laboratory demonstrations to practical applications.

Fluoropolymers (PVDF, PTFE, HFP-VDF) appear in both journals and patents, typically as materials chosen for chemical resistance, thermal stability, repeated cycling, and durability.[403] In TES, these polymers are rarely used because they store large amounts of heat themselves; instead, they are used for radiative cooling, and as supporting matrices for PCMs.[404, 405]

Bio-inspired polymers (PDA and related systems), conducting polymers (PEDOT, PPy, and PANI), and polyamides (e.g. Nylon 6) appear predominantly in the academic literature, reflecting an emphasis on early-stage, exploratory research aimed at multifunctional TES materials that combine heat storage with electrical, adhesive, or structural performance enhancements.[406, 407] Conversely, synthetic rubbers (SBS, SBR) appear only in patents, indicating industrial innovation in flexible PCMs.[408]

This comprehensive analysis reveals that academic research is exploring novel functional combinations and industry is optimizing cost-effective encapsulation and shape-stabilization strategies. The strong patent activity across multiple polymer classes indicates thermal storage is transitioning from material discovery to system-level optimization and commercialization.

4.3 Summary and Outlook

In summary, polymers are becoming increasingly essential to modern energy-storage systems, as shown by rising research and patent activity. Their tunability, mechanical flexibility, and ability to support ion/electron transport make them vital components across different kinds of energy storage systems–batteries, capacitors, TES, and chemical energy storage. Batteries dominate this landscape, with polymers serving as separators, binders, electrolytes, and interfacial stabilizers. In LIBs, polyolefins remain foundational separator materials, while fluoropolymers are widely used as chemically robust binders. Emerging trends highlight natural polymers such as CMC-Na, as well as PEG derivatives, acrylic polymers, and synthetic rubbers, which support next-generation LIBs. Beyond lithium-ion systems, polymer use is diversifying across next generation batteries like solid-state, sodium-ion, flow, zinc-ion, and metal-air, with academia exploring high-performance membranes and electrolytes while industry gravitates toward scalable materials such as fluoropolymers, and polyolefins. Similar patterns appear in capacitors and TES, where commercially dominant polymers include polyolefins, PET, PEG, and vinyl polymers, supported by ongoing academic exploration into conducting polymers, bio-inspired polymers, and multifunctional composites. Chemical energy storage remains the least developed sector, with minimal polymer diversity and only small patent activity dominated by polyamides and emerging epoxy-based systems.

Overall, the field is transitioning from broad exploratory research toward targeted, application-driven polymer development, especially in batteries, capacitors, and TES. Industry increasingly prioritizes polymers that offer manufacturability, stability, and compatibility with existing production lines, while academic research continues pushing the boundaries of advanced solid-state electrolytes, high-performance dielectric films, and multifunctional thermal-storage composites. Looking ahead, polymers are poised to become critical enablers of next-generation energy-storage technologies, supporting safer solid-state batteries, high-energy capacitors, sustainable polymer processing, and durable TES systems, while unlocking new opportunities in hydrogen and chemical storage as those sectors mature.

5. Sustainable Polymers: Versatile Applications with Environmental Stewardship

5.1 Evolving Research Landscape: Publication Trends and Corporate Patent Dynamics

Sustainable polymers emerged as a significant focus area in our NLP analysis of both journal articles and patent families. This rapidly expanding field has become a critical research and industrial priority, driven by urgent environmental challenges and global transitions toward circular economy principles. Our comprehensive analysis examines the evolving landscape of sustainable polymer technologies through systematic evaluation of CAS-indexed publications spanning academic literature and patent families from 2015-2025.

To establish a comprehensive view of sustainable polymer publication trends, we identified documents containing sustainable polymer-related keywords, or documents indexed with sustainable polymer substances. The result yielded a dataset of approximately 285,000 publications across the study period.

Figure 30 illustrates the annual publication distribution and composition from 2015 to 2025 for documents identified using both sustainable polymer-related keywords, and documents indexed with sustainable polymer-related keywords. It demonstrates consistent expansion in sustainable polymer research throughout this period, with journal articles increasing by 53% (from 6,407 to 9,830 by 2024) and patent families growing by 37% (from 15,765 to 21,637 by 2024). The predominant patent-to-journal ratio of 2.5:1 (reflected in the 71%:29% distribution shown in the pie chart) indicates robust commercial development significantly outpacing academic research. Both sectors experienced synchronized growth acceleration during 2020-2022, coinciding with heightened global sustainability initiatives.

Leading corporate patent assignees and geographical distribution of corporate enterprise patents are presented in **Figure 31**. The sustainable polymer commercial landscape is

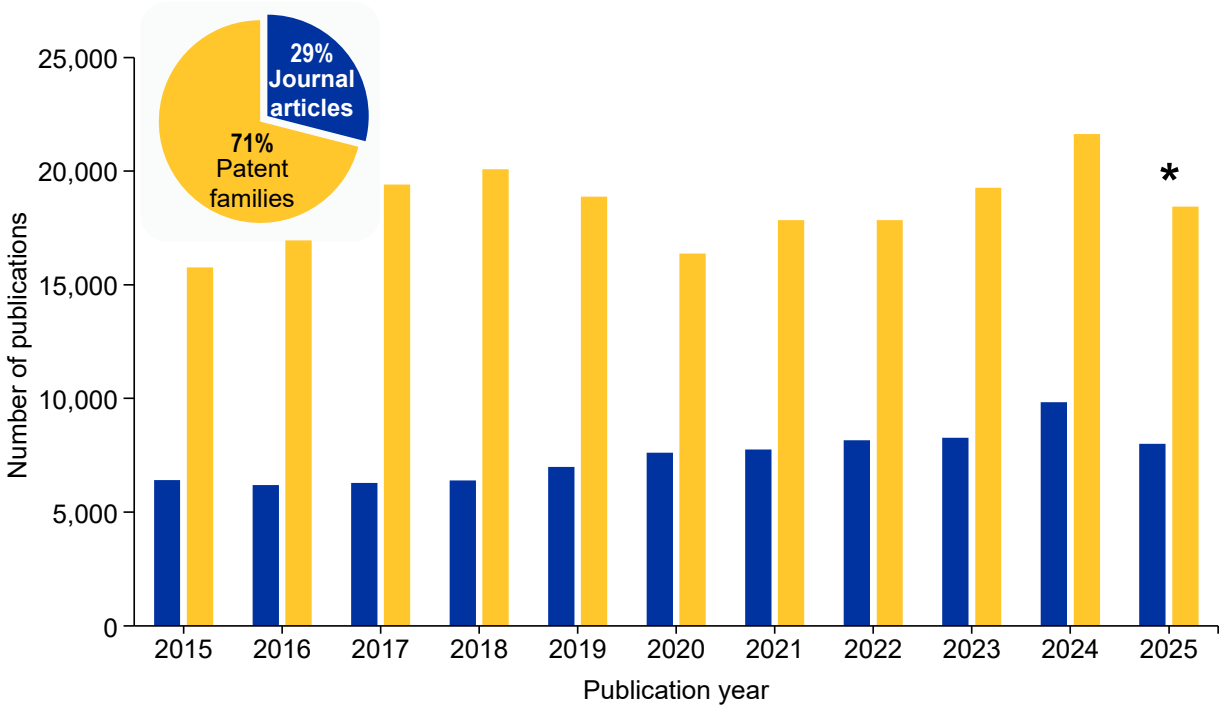


Figure 30. Trends for publications containing sustainable polymer-related keywords and sustainable polymer substances. Data includes journal and patent publications for the period 2015-2025 from the CAS Content Collection. *Data only for the months January to November in 2025.

dominated by major enterprises concentrated in specific geographic regions. Analysis of patent activity reveals distinct patterns of corporate investment and strategic positioning across global markets. Chinese corporations have established overwhelming leadership in sustainable polymer technologies, controlling 54% of corporate patents in this sector. Sinopec stands as the global frontrunner with 3,409 patents—nearly tripling the output of its nearest competitor, CNPC with 1,227 patents. This Chinese dominance spans both state-owned energy conglomerates (Sinopec, CNPC) and specialized chemical manufacturers (Wanhua Chemical Group, Kingfa Science and Technology), indicating coordinated national interest in sustainable polymer development. Japanese enterprises have carved out significant technological niches, collectively securing 10% of global corporate patents. Toray Industries, Mitsubishi Chemical, Kuraray, and Fujifilm Holdings leverage Japan's traditional strengths in advanced materials engineering and precision manufacturing to establish leadership positions in high-performance sustainable polymers. European commercial activity centers on established chemical corporations like BASF and Arkema, while Dow represents the primary American commercial presence. The substantial "Others" category (17% of patents) reveals diverse innovation sources beyond these major players, suggesting opportunities for emerging competitors in specialized market segments. This distribution, illustrated in **Figure 31**, demonstrates a concentrated commercial landscape where regional industrial policies and corporate specialization significantly influence sustainable polymer innovation trajectories and market development.

5.2 Sustainable Polymers in Emerging Polymer Applications from Patents

We now turn our attention to how sustainable polymer materials are being deployed across diverse industrial applications. This analysis examines both prominent and emerging sustainable polymer technologies within key commercial sectors including electronics and semiconductors, textiles, adhesives and coatings, construction, packaging, etc. By mapping specific polymer innovations to their target applications,

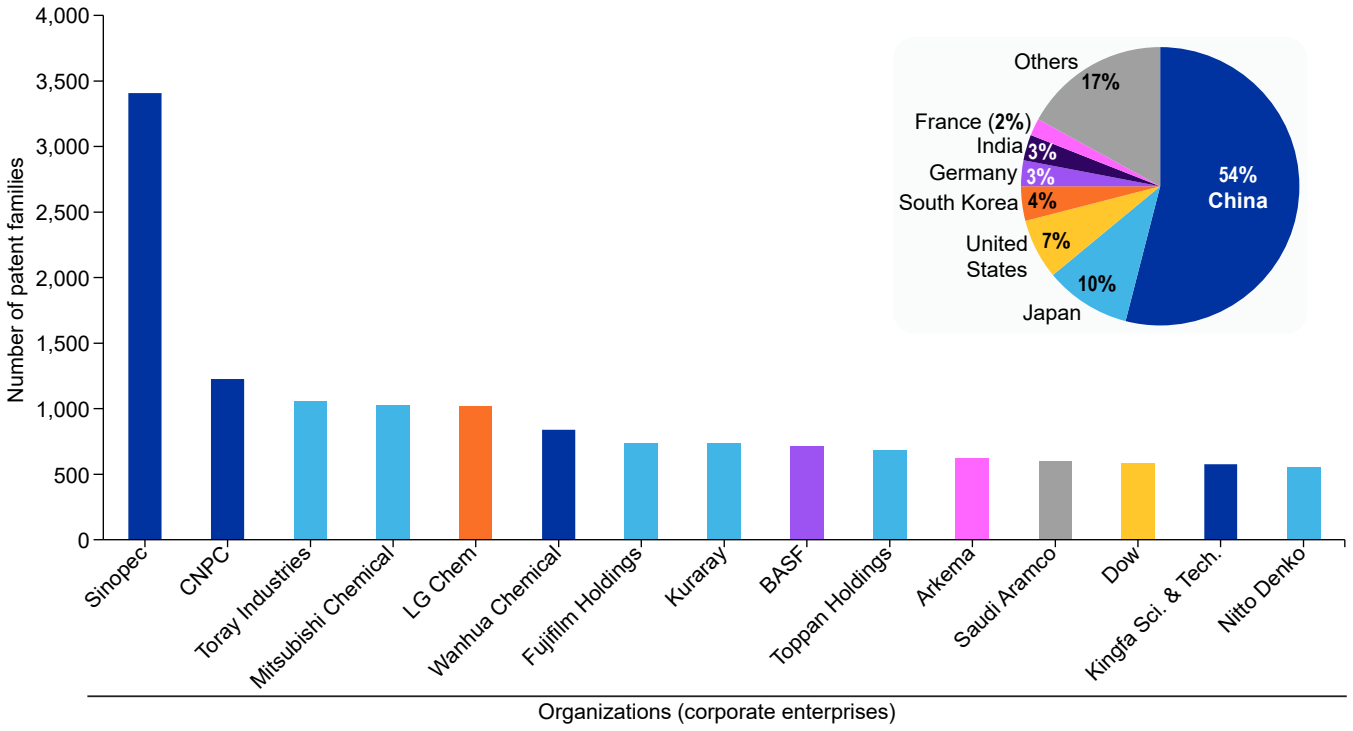


Figure 31. Leading corporate enterprises by patent volume in sustainable polymers with the inset pie chart illustrating the country/region-wise distribution. Data includes patent families from the CAS Content Collection for the period 2015-2025.

we can identify where sustainable alternatives are gaining commercial traction, which sectors present the greatest barriers to adoption, and where technological gaps offer opportunities for future development.

Figure 32 illustrates the number of patent publications in the nine emerging application areas. Electronics and semiconductors, textiles and apparel, and adhesives and coatings are the three major applications followed by construction and building, and packaging and consumer products. The most prevalent polymer substance classes within these nine emerging applications are presented in **Figure 32**. It further presents the number of patent families containing these substance classes in each of the applications and their growth rates for the period 2020-2024. Across the nine emerging applications, there is significant overlap in the prevalent polymer substances classes, and they all fall within the nine substance classes discussed below.

Polyoxyalkylenes are present in the highest number of patent families in these applications. Polyoxyalkylenes are predominantly biodegradable polymers synthesized by the polymerization of alkylene oxides which are typically derived from petroleum-based feedstocks. Polyoxyalkylenes' dominance in textiles reflects their role as hydrophilic segments in moisture-wicking fabrics[409, 410] and breathable membranes.[411] In electronics, polyoxyalkylenes function as flexible spacers in conductive composite[412] and as processing aids for semiconductor encapsulants.[413] The exceptional 57% growth of polyoxyalkylenes in energy applications, though representing fewer patents (2,912), indicates emerging opportunities in solid electrolytes[414] and separator membranes for next-generation batteries.[415]

PLA based polyesters and their fibers are one of the most prevalent substance classes within the emerging applications. PLA based polyesters are primarily derived from renewable biomass, which are fermented by bacteria to produce the necessary lactic acid monomers. Lactic acid-based polyesters show remarkable growth momentum, with biomedical applications achieving 96% growth despite moderate patent volumes. This reflects the material's biocompatibility and controlled degradation kinetics, making it ideal for drug delivery systems[416] and temporary implants.[417] The 88% growth in energy storage applications suggests promising developments in biodegradable battery components,[418] while the 75% growth in packaging aligns with circular economy demands for compostable food containers.[419]

PHAs are a class of natural, biodegradable polyesters synthesized by various microorganisms as intracellular granules for carbon and energy storage. PHAs represent the most dynamic growth story, with safety/environmental applications showing an unprecedented 580% increase. This explosive growth, though from a small base (52 patents), indicates breakthrough innovations in environment friendly osmosis membranes[420] and composites.[421] PHAs' natural origin and complete biodegradability position them as premium solutions where environmental impact is paramount.

Cellulosic fibers are primarily derived from plant-based sources, including seed hairs, woody materials, and bast fibers, which are all composed of the natural polymer cellulose. Cellulosic fibers demonstrate exceptional growth in safety applications (173% growth), likely driven by flame-retardant treatments[422] and protective equipment innovations.[423] Their 91% growth in construction reflects increasing adoption in bio-based insulation materials and structural composites, where cellulose's inherent strength and thermal properties provide sustainable alternatives to synthetic materials.

Natural rubber shows remarkable 247% growth in safety applications, primarily as vibration dampening materials[424] in protective equipment. Natural rubber is primarily sourced from the milky white latex of Hevea brasiliensis tree. Its superior elastic recovery and tear resistance make it essential for applications requiring repeated deformation cycles. In electronics (11% growth), natural rubber serves as flexible substrates for electronics,[425] where its inherent stretchability enables conformal contact with

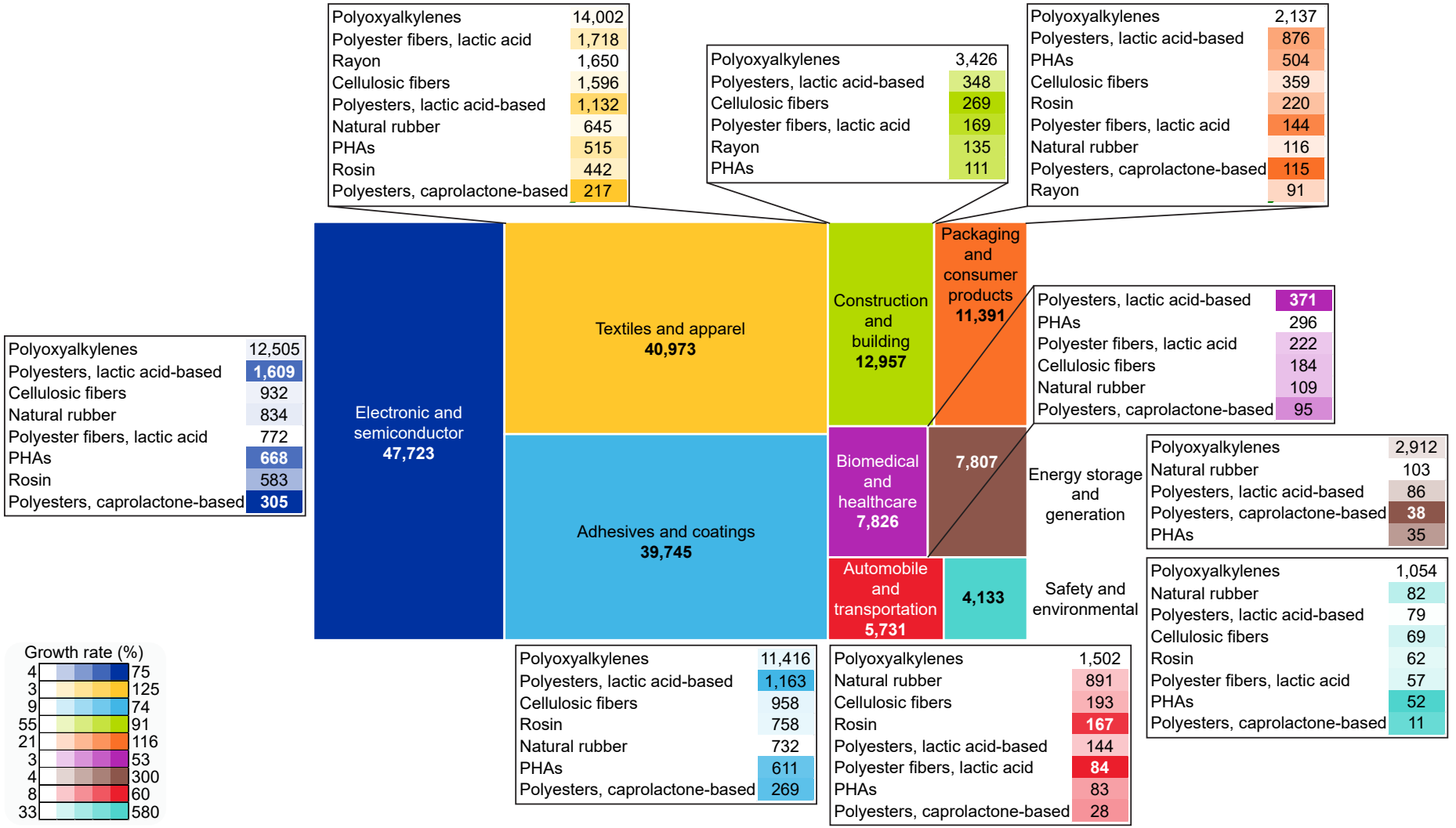


Figure 32. Sustainable polymer classes across 9 emerging applications and the most prevalent substance classes and number of patent families containing these substance classes in these emerging applications. The cells are color coded according to the growth rate of the publications during the period 2020-2024 as shown in the legend. Data includes patent families from the CAS Content Collection for the period 2015-2025.

curved surfaces while maintaining electrical insulation properties.

Rosin is a natural solid resin primarily obtained by distilling the sap harvested from living pine trees. Rosin-based polymers show strong performance in adhesives (17% growth, 758 patents), where they serve as tackifying agents in pressure-sensitive adhesives.[426] Their aromatic structure provides excellent adhesion to various substrates while maintaining removability. In electronics applications (29% growth), rosin is used in the preparation of conductive pastes.[427]

Rayon maintains steady growth in textiles (3% growth, 1,650 patents), serving as moisture-absorbing fibers in technical textiles.[428] Rayon is a semi-synthetic fiber manufactured by chemically regenerating cellulose derived from natural plant sources. Its high surface area and hydrophilic nature make it ideal for filtration media and absorbent products. In construction applications (66% growth), rayon functions as reinforcing fibers in sound-proof structures.[429]

PCL is a biodegradable synthetic polyester typically produced through the ring-opening polymerization of epsilon-caprolactone, a monomer derived from petrochemical precursors like cyclohexanone. PCL exhibits exceptional growth rates reaching 500% in environmental applications, driven by its role as controlled-release matrices for environmental remediation.[430] Its slow degradation kinetics enable sustained release of active compounds for soil treatment applications. In biomedical applications (53% growth), PCL serves as long-term implant materials, where its extended degradation timeline (2-3 years) matches tissue remodeling requirements.[431]

The patent landscape indicates that sustainable polymers are transitioning from niche applications to mainstream industrial adoption. The combination of regulatory pressure, technological maturity, and demonstrated commercial viability positions this field for sustained growth, with particular opportunities in high-growth, low-volume applications that may represent tomorrow's dominant markets.

After examining the major polymer classes in patent families across applications, we now analyze specific individual polymer substances in both the journal and patent publications using four criteria:

Prevalence - Identifies dominant substances with the highest volumes, indicating established commercial importance and research maturity.
Patent concentration - Reveals substances with high patent-to-journal ratios, signaling strong commercial development focus and potential near-term market opportunities.
Growth rate (2020-2024) - Highlights rapidly emerging substances experiencing accelerated research and development activity, indicating future market potential and technological momentum.
Citation impact - Identifies substances with high average citations per journal publication, revealing materials of significant academic interest that may represent the next generation of commercial technologies pending successful research validation.

This multi-dimensional analysis provides a comprehensive view of the polymer substance landscape in the emerging applications: established leaders (prevalence), immediate commercial opportunities (patent concentration), emerging substances (growth), and future breakthrough candidates (citation impact).

5.2.1.Sustainable Polymers in Electronics and Semiconductor Applications

The electronics and semiconductor sector represents a rapidly evolving application domain for sustainable polymers, where environmental regulations, miniaturization demands, and performance requirements converge to drive innovation toward bio-based alternatives. **Figure 33** presents the sustainable polymer substances in electronics and semiconductor applications categorized based their prevalence, % of patents, growth (2020-2024), and citations per publication.

The most prevalent polymers in electronics and semiconductor applications are presented in **Figure 33A**. PEG dominates the landscape, primarily functioning as a solid

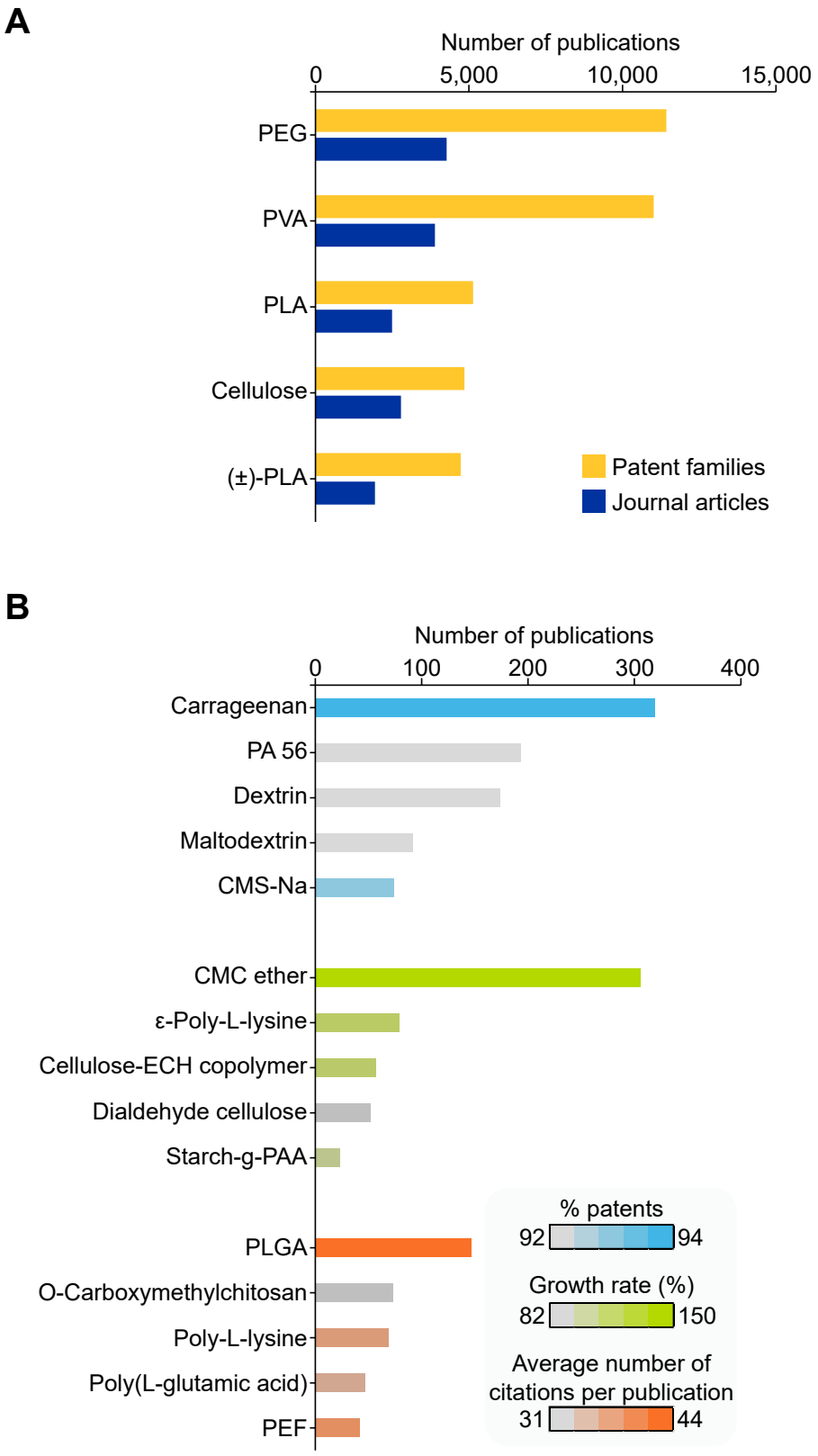


Figure 33. Top 5 sustainable polymer substances in electronics and semiconductor applications based on (**A**) their prevalence, and (**B**) % of patents, growth (for the period 2020-2024), and average citations per publication. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

polymer electrolyte in flexible batteries and supercapacitors.[432] Its ether linkages provide ionic conductivity while maintaining electrochemical stability across wide temperature ranges. PEG's role as a processing aid in conductive polymer formulations enables uniform dispersion of carbon nanotubes and graphene, critical for flexible electronic applications where mechanical integrity must be maintained during repeated bending cycles.[433] PVA shows comparable commercial interest, serving as a dielectric layer in organic thin-film transistors (OTFTs).[434] Its excellent film-forming properties and tunable dielectric constant through crosslinking enable precise control of device performance. Cellulose maintains strong as a flexible substrate material for printed electronics.[435] Its fibrous structure provides mechanical reinforcement while chemical modifications enable controlled surface energy for optimal ink adhesion. Cellulose derivatives serve as transparent conductive film matrices, where high aspect ratio fibers create percolation networks for electrical conductivity while maintaining optical transparency.[436]

The indexed substances with high percentage of patents are presented in **Figure 33B**. Carrageenan exhibits 94% patent concentration, indicating intensive commercial development as a gel electrolyte in biocompatible sensors. Its thermoreversible gelation mechanism enables processing at moderate temperatures while providing ionic conductivity suitable for wearable health monitoring devices.[437] The sulfate groups in carrageenan structure facilitate ion transport while maintaining biocompatibility for skin-contact applications. Poly[imino-1,5-pentanediylimino(1,6-dioxo-1,6-hexanediyl)] (PA56) shows 92% patent focus, functioning as a high-temperature dielectric material in power electronics applications.[438] It provides thermal stability exceeding 300°C while maintaining low dielectric loss, essential for electric vehicle inverters and renewable energy power conversion systems where sustainable materials address end-of-life recycling concerns. Dextrin demonstrating 92% patent concentration, is used as a biodegradable additive in the preparation of films for OLEDs.[439] Its controlled degradation kinetics enable development of transient electronics for environmental monitoring, where devices dissolve harmlessly after predetermined operation periods. Dextrin is used as a component of binders for capacitors.[440]

The substances with high growth during the period 2020-2024 are presented in **Figure 33B**. Cellulose carboxymethyl ether (CMC ether) exhibiting exceptional 150% growth, are used in hydrogel electrolytes for high-voltage supercapacitors.[441] The carboxymethyl modification introduces ionic functionality while maintaining cellulose's mechanical properties, enabling development of sustainable separators for capacitors.[442] It is also used as a sustainable matrix to impart flexibility in conducting composites for pressure sensors.[443] ε-Poly-L-lysine shows 114% growth as an antimicrobial coating for electronic components.[444] ε-Poly-L-lysine is used as a biocompatible polymer scaffold in the preparation of chemosensors.[445] Cellulose-epichlorohydrin copolymer (Cellulose-ECH copolymer) demonstrates 112% growth, owing to its superior mechanical, thermal, chemical stability, electrical conductivity. The quaternary ammonium groups introduced through epichlorohydrin crosslinking provide hydroxide ion conductivity while the cellulose backbone ensures mechanical stability. Its role as a sustainable membrane material addresses the environmental impact of conventional perfluorinated polymers in clean energy applications such as LIBs.[446] Cellulose-ECH copolymer based hydrogels are used as biocompatible soft electrode materials for next generation bio-interfacing and flexible implantable devices.[447]

The polymers present in most cited publications are presented in **Figure 33B**. Poly(lactic-co-glycolic acid) (PLGA) leads with 44 average citations, reflecting its significance as a biodegradable substrate for transient electronics.[448] The tunable degradation kinetics through lactide/glycolide ratio adjustment enables precise control of device lifetime, critical for implantable medical electronics where controlled dissolution prevents long-term bioaccumulation.[449] PLGA's role as a drug-eluting electronic platform demonstrates convergence of

sustainable materials with advanced healthcare technologies.[450] PEF shows 39 average citations, representing sustainable substrate alternatives to fossil fuel based polymer substrates for flexible electronics.[451] Derived from biomass-based furandicarboxylic acid, PEF provides superior oxygen and moisture barrier properties compared to conventional polyesters.[452] Poly-L-lysine exhibits 37 average citations, primarily studied for bioelectronic interface applications.[453, 454] Its cationic nature enables strong adhesion to negatively charged biological surfaces while maintaining biocompatibility enabling biosensor applications.[455]

5.2.2. Sustainable Polymers in Textiles and Apparel Applications

The textiles and apparel sector represents a transformative application domain for sustainable polymers, where consumer demand for eco-friendly products, regulatory pressures on microplastic pollution, and performance requirements drive innovation toward bio-based and biodegradable alternatives. **Figure 34** presents the sustainable polymer substances in textiles and apparels applications categorized based on their prevalence, % of patents, growth, and citations per publication. Analysis of patent families and journal publications reveals distinct patterns in commercial development, research priorities, and emerging technological opportunities across various sustainable polymer platforms.

The most prevalent substances are presented in **Figure 34A**. PEG leads the commercial landscape, primarily functioning as a moisture-wicking agent in performance textiles. Its hydrophilic ether linkages enable rapid moisture transport from skin to fabric surface, while the polymer's low toxicity ensures skin compatibility in athletic wear.[456] PEG serves as a fiber spinning aid in melt-processing of biodegradable fibers, reducing melt viscosity and preventing thermal degradation during high-temperature extrusion of PLA and other thermally sensitive biopolymers.[457] PVA demonstrates strong research interest with substantial commercial development, serving as a water-soluble fiber for temporary textile structures.[458] Its exceptional film-forming properties enable production of biodegradable nonwoven fabrics for medical textiles, where controlled dissolution removes temporary supports without residual contamination. [459] PVA functions as a sizing agent in sustainable weaving processes, providing temporary yarn strength during fabric formation before complete removal through aqueous washing, eliminating petroleum-based sizing chemicals.[460] PLA maintains balanced research-commercial development, representing the primary biodegradable synthetic fiber platform.[461] Its thermoplastic properties enable conventional melt-spinning processes while providing complete compostability under industrial conditions. PLA's role as a microfiber alternative addresses ocean pollution concerns, as biodegradable microfibers released during washing degrade harmlessly in marine environments, contrasting with persistent petroleum-based microplastics.[462]

The substance with high percentage of patents are presented in **Figure 34B**. Hydroxypropyl methyl cellulose (HPMC) exhibits 93% patent concentration, indicating intensive commercial development as a textile printing thickener.[463] Its pseudoplastic rheological behavior provides excellent print definition while maintaining biodegradability, replacing synthetic thickeners in sustainable textile printing processes. HPMC functions as a temporary binder in nonwoven production, enabling fiber consolidation during web formation before controlled dissolution, essential for producing biodegradable hygiene products and medical textiles.[464] Dextrin shows 96% patent focus, primarily utilized as a natural textile starch for fabric finishing. Its branched glucose structure provides controlled stiffness and wrinkle resistance while maintaining complete biodegradability.[465] Dextrin serves as a eco-friendly fabric softener, where enzymatic modification creates amphiphilic structures that reduce fiber-fiber friction without quaternary ammonium compounds, addressing both performance and environmental requirements.[466] Carrageenan demonstrates 93% patent concentration, functioning as a gel-forming agent in textile dyeing processes.[467] Its thermoreversible gelation mechanism enables

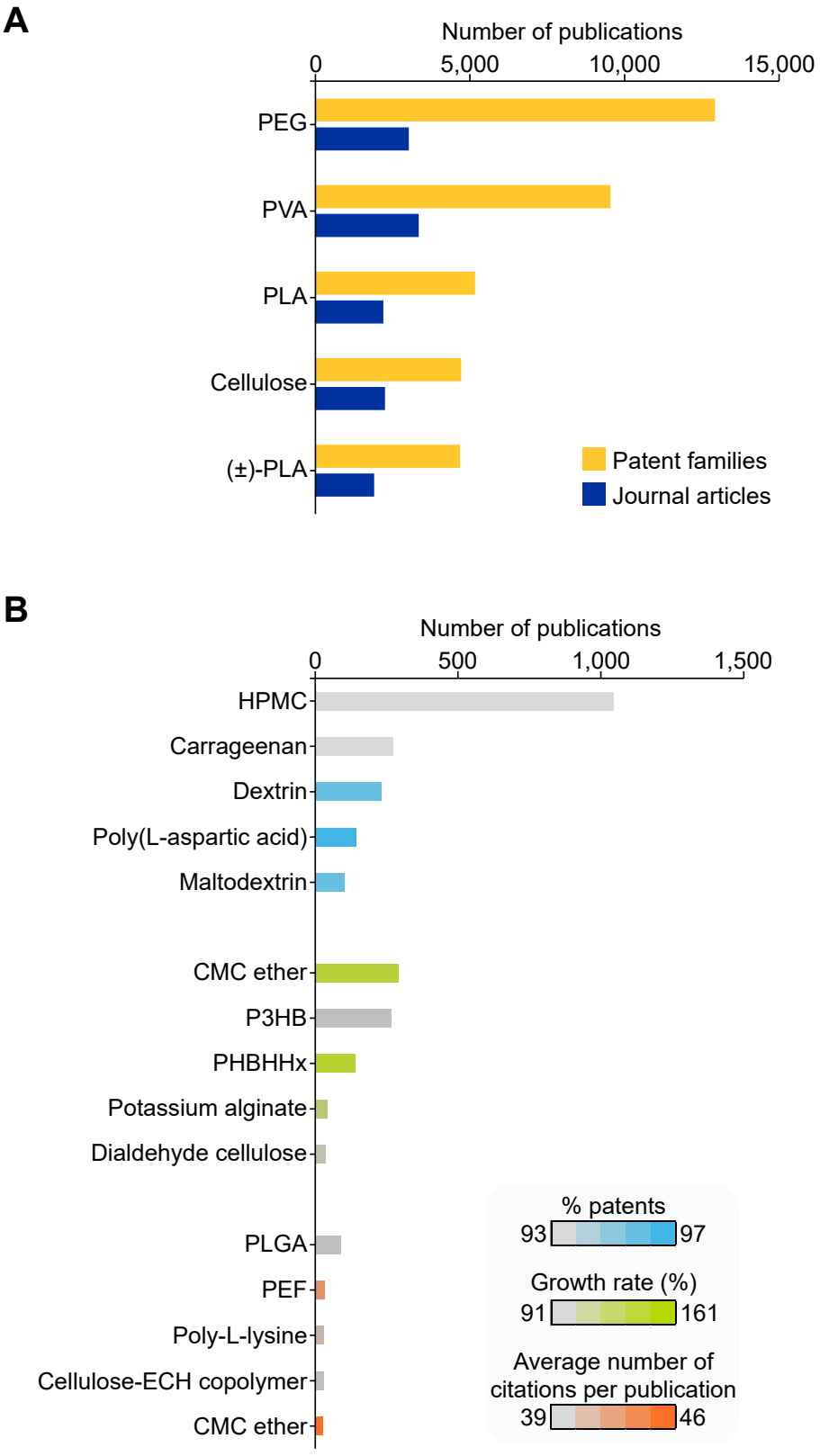


Figure 34. Top 5 sustainable polymer substances in textiles and apparels applications based on their (**A**) prevalence and (**B**) % of patents, growth (for the period 2020-2024), and average citations per publication. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

controlled dye penetration and fixation while reducing water consumption through gel-phase dyeing techniques. Carrageenan's role as an antimicrobial textile treatment leverages its natural bioactivity to prevent odor-causing bacterial growth in athletic wear without synthetic biocides.[468]

The substances with high growth during the period 2020-2024 are presented in **Figure 34B**. PHBHHx exhibits exceptional 192% growth, representing next-generation marine-biodegradable synthetic fibers. Hexanoate reduces crystallinity compared to poly(3-hydroxybutyrate) (P3HB), improving fiber flexibility and processability while maintaining complete biodegradation in seawater. PHBHHx functions as a sustainable microfiber alternative for outdoor apparel, where fiber fragments released during use degrade harmlessly in natural environments.[469, 470] CMC ether shows 161% growth as an ion-exchange fiber treatment. The carboxymethyl modification introduces anionic functionality while maintaining cellulose's mechanical properties, enabling development of antimicrobial textiles through controlled metal ion binding.[471] Its role as a moisture-responsive fiber coating leverages controlled swelling behavior to create adaptive textiles that respond to humidity changes.[472] P3HB demonstrates 91% growth, functioning as a biodegradable coating for natural fibers. Its thermoplastic properties enable melt-coating processes while providing water resistance and dimensional stability to cotton and wool textiles.[473] P3HB serves as a sustainable alternative to fluorinated treatments, providing stain resistance and water repellency without persistent environmental contamination.[474]

The substances which are present in most cited publications are shown in **Figure 34B**. CMC ether leads with 46 average citations, reflecting its significance as a multifunctional textile treatment platform. 2,5-furandicarboxylic acid, polymer with 1,2-ethanediol (PEF) shows 43 average citations, representing bio-based polyester fibers with enhanced properties. Derived from biomass-based furandicarboxylic acid, PEF provides superior mechanical properties and thermal stability compared to PET while maintaining recyclability.[475] Research emphasizes fiber spinning optimization and blend compatibility with natural fibers for high-performance sustainable textiles.[476]

5.2.3.Sustainable Polymers in Adhesives and Coatings Applications

The adhesives and coatings sector represents a critical application domain for sustainable polymers, where environmental regulations and performance demands drive innovation toward bio-based and biodegradable alternatives. **Figure 35** presents the sustainable polymer substances in adhesives and coating applications categorized based their prevalence, % of patents, growth, and citations per publication.

The most prevalent substances are presented in **Figure 35A**. PVA dominates both patent landscapes, functioning as a water-soluble binder in eco-friendly adhesive formulations. Its exceptional film-forming properties and hydrogen bonding capability make it ideal for paper and packaging adhesives, where it provides strong initial tack and controlled water sensitivity.[477] In coatings applications, PVA serves as a rheology modifier and protective colloid, stabilizing emulsion systems while providing barrier properties against oils and greases.[478] PEG shows substantial commercial interest, primarily functioning as a plasticizer and chain extender in polyurethane adhesives.[479] Its hydrophilic nature and low toxicity enable formulation of water-based adhesive systems with reduced volatile organic compound emissions.[480] PEG's role as a phase transfer catalyst in coating formulations facilitates uniform dispersion of inorganic fillers and pigments, improving coating durability and appearance.[481] Cellulose maintains strong presence across both domains, serving as a natural thickening agent and film-forming polymer. Its fibrous structure provides mechanical reinforcement in adhesive joints, while chemical modifications enable tunable solubility and adhesion properties. In coatings, cellulose derivatives function as anti-settling agents for pigment suspensions, preventing phase separation during storage while maintaining application viscosity.[482]

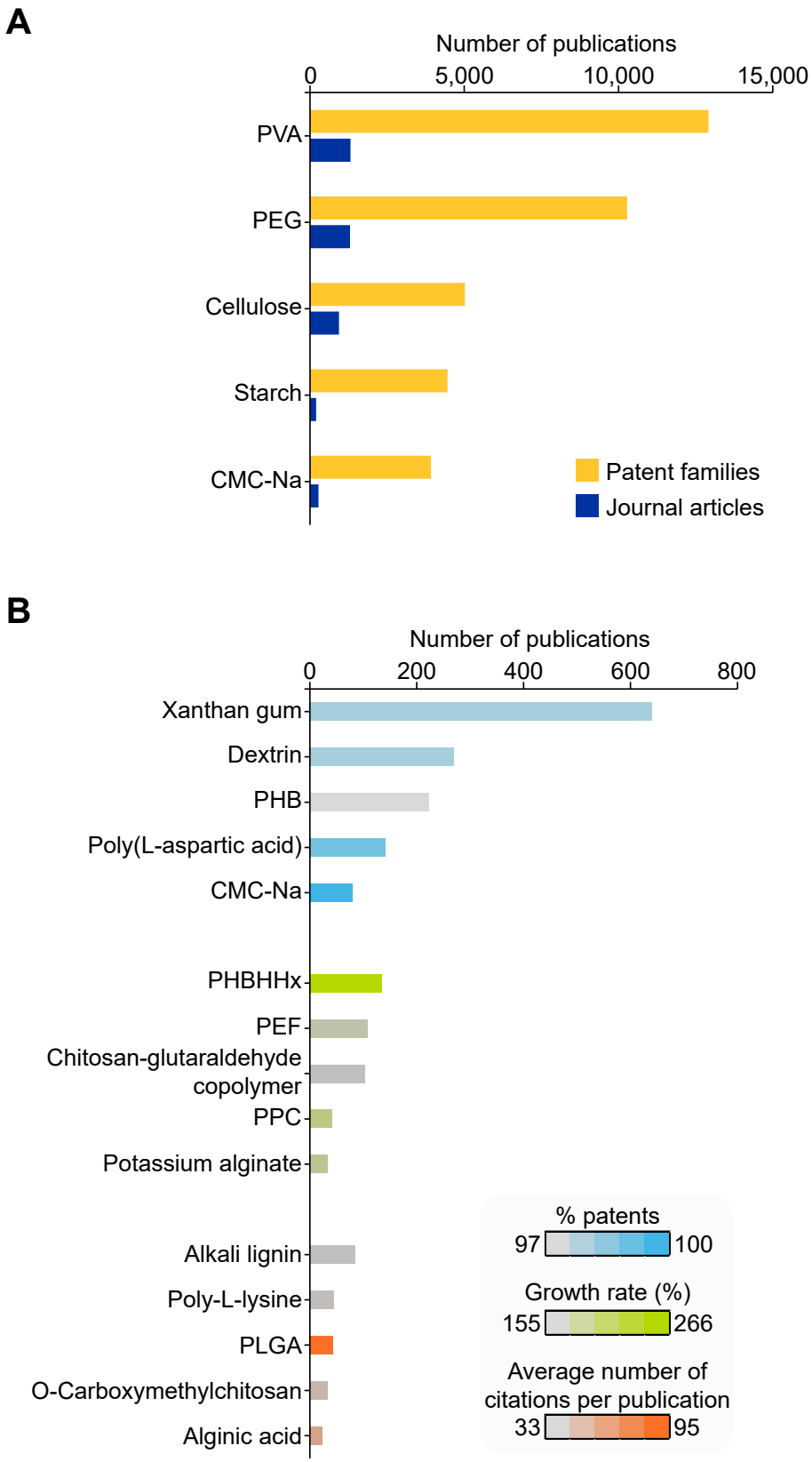


Figure 35. Top 5 sustainable polymer substances in adhesives and coating applications based on their (**A**) prevalence and (**B**) % of patents, growth, and average citations per publication. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

The substances present in high percentage of patents are presented in **Figure 35B**. Xanthan gum exhibits 98% patent concentration, indicating strong commercial development as a rheological modifier in water-based adhesive systems. Its pseudoplastic behavior provides excellent application properties—high viscosity at rest prevents dripping, while shear-thinning enables smooth application.[483] The microbial origin and biodegradability address environmental concerns while maintaining performance comparable to synthetic thickeners. Dextrin shows 98% patent focus, primarily utilized as a natural tackifier in pressure-sensitive adhesives.[484] Its branched glucose structure provides controlled tack development and removability, essential for temporary bonding applications. Dextrin's water solubility enables easy cleanup and recycling of bonded substrates, addressing circular economy requirements in packaging applications. Poly(hydroxybutyrate) (PHB) demonstrates 97% patent concentration, functioning as a biodegradable matrix polymer in coating formulations.[485] Its thermoplastic properties enable melt processing while maintaining complete biodegradability under composting conditions. PHB's barrier properties against water vapor and oxygen make it suitable for protective coatings on biodegradable packaging materials.

The substances which showed high growth during the period 2020-2024 are presented in **Figure 35B**. PHBHHx exhibits exceptional 266% growth, representing next-generation flexible biodegradable coatings.[486] The hexanoate comonomer reduces crystallinity compared to PHB homopolymer, improving flexibility and processability. PHBHHx functions as a marine-degradable barrier coating for ocean-exposed applications, addressing plastic pollution concerns while maintaining protective properties.[487] PEF shows 167% growth as a bio-based polyester for high-performance coatings. Derived from biomass-based furandicarboxylic acid, PEF provides superior barrier properties compared to petroleum-based polyesters. Its role as a UV-resistant topcoat in outdoor applications leverages the furan ring's inherent photostability while reducing reliance on synthetic UV absorbers.[488] Chitosan-glutaraldehyde copolymer demonstrates 155% growth, functioning as an antimicrobial coating agent.[489] The crosslinked structure provides controlled release of antimicrobial chitosan segments while maintaining coating integrity. This copolymer serves as a bioactive surface treatment for medical devices and food packaging, where sustained antimicrobial activity prevents contamination without leaching toxic compounds.

The polymers present in the most cited publications are presented in **Figure 35B**. PLGA leads with 95 average citations, reflecting its significance as a controlled-release coating system. The tunable degradation kinetics through lactide/glycolide ratio adjustment enables precise control of active ingredient release rates. PLGA's role as a drug-eluting coating on medical implants demonstrates the convergence of sustainable materials with advanced healthcare applications.[490] Alginic acid shows 55 average citations, primarily studied for its gel-forming properties in aqueous coating systems. Its calcium-responsive gelation mechanism enables development of smart coatings that respond to environmental conditions.[491] Alginic acid functions as a self-healing coating matrix, where calcium ion migration repairs microscopic defects, extending coating service life.[492] O-Carboxymethylchitosan exhibits 41 average citations, representing advanced pH-responsive coating technology. The carboxymethyl modification enhances water solubility while maintaining chitosan's inherent antimicrobial properties.[493]

5.2.4. Sustainable Polymers in Packaging and Consumer Products

Following the detailed analysis of the top three applications with the highest number of publications, we analyzed the packaging and consumer products applications due to the significant interest in sustainable packaging in recent years. The packaging and consumer products sector represents the most visible application domain for sustainable polymers, where regulatory pressures on single-use plastics, consumer environmental awareness, and circular economy initiatives drive rapid

innovation toward bio-based and biodegradable alternatives. **Figure 36** presents the sustainable polymer substances in packaging and consumer products categorized based on their prevalence, % of patents, growth, and citations per publication.

The most prevalent substances are presented in **Figure 36A**. PVA dominates commercial development, primarily functioning as a water-soluble packaging film for detergent pods and agricultural applications.[494] Its exceptional film-forming properties and controlled water solubility enable single-dose packaging that dissolves completely during use, eliminating packaging waste. PVA serves as a barrier coating for paper-based packaging, providing grease and moisture resistance while maintaining recyclability through standard paper recycling processes, addressing the need for sustainable alternatives to plastic-coated paperboard.[495] Starch demonstrates strong commercial interest, functioning as a biodegradable foam packaging material.[496] Its thermoplastic processing capability when plasticized enables production of expanded packaging foams that provide cushioning protection while composting completely within 90 days. Starch-based polymers serve as edible packaging films for food applications, where controlled permeability to oxygen and moisture extends shelf life while the packaging itself can be consumed or composted, eliminating waste streams entirely.[497] PLA maintains balanced research-commercial development, representing the primary rigid packaging alternative to petroleum-based plastics. Its thermoplastic properties enable conventional processing on existing equipment while providing complete industrial compostability.[498] PLA functions as a transparent barrier film for food packaging, where controlled crystallization provides oxygen barrier properties comparable to PET while maintaining clarity for product visibility and consumer acceptance.[499]

Substances with high percentage of patents are presented in **Figure 36B**. Hydroxymethylcellulose (49 patents) functions as a controlled-release coating system for pharmaceutical and nutraceutical packaging. Its thermoplastic behavior and pH-responsive dissolution enable development of enteric coatings that protect active ingredients during storage while ensuring controlled bioavailability. The hydroxymethyl modification provides enhanced water solubility compared to native cellulose, enabling precise dissolution timing for targeted delivery applications.[500] Lignosulfonic acid (42 patents) serves as a natural dispersant and binder in paper-based packaging formulations.[501] As a byproduct of sulfite pulping processes, it provides cost-effective rheological modification while enhancing wet-strength properties in corrugated packaging. Its aromatic structure offers natural antioxidant activity, protecting packaged contents from oxidative degradation while maintaining complete biodegradability. Glycolide polymer (37 patents) represents high-performance biodegradable barrier films for food packaging applications. The rapid hydrolytic degradation of polyglycolide enables development of time-sensitive packaging that maintains barrier properties during shelf life before degrading completely under composting conditions.[502] Its high crystallinity provides excellent gas barrier properties comparable to conventional synthetic films.[503]

Polymers which show high growth during the period 2020-2024 are presented in **Figure 36B**. CMC ether exhibits exceptional 700% growth, due to its excellent barrier properties and mechanical strength.[504] PHBHHx shows 170% growth as a flexible biodegradable packaging film.[505] The hexanoate comonomer reduces crystallinity compared to PHB homopolymer, improving flexibility and heat-sealability essential for flexible packaging applications. PHBHHx functions as a marine-biodegradable packaging material for products used in marine environments, where packaging fragments degrade harmlessly in seawater rather than accumulating as persistent pollution.[506] Ethylcellulose demonstrates 119% growth, functioning as a moisture barrier coating for sensitive products.[507] Its hydrophobic character provides excellent water vapor barrier properties while maintaining biodegradability under appropriate conditions. Ethylcellulose serves as a controlled-release matrix for active packaging

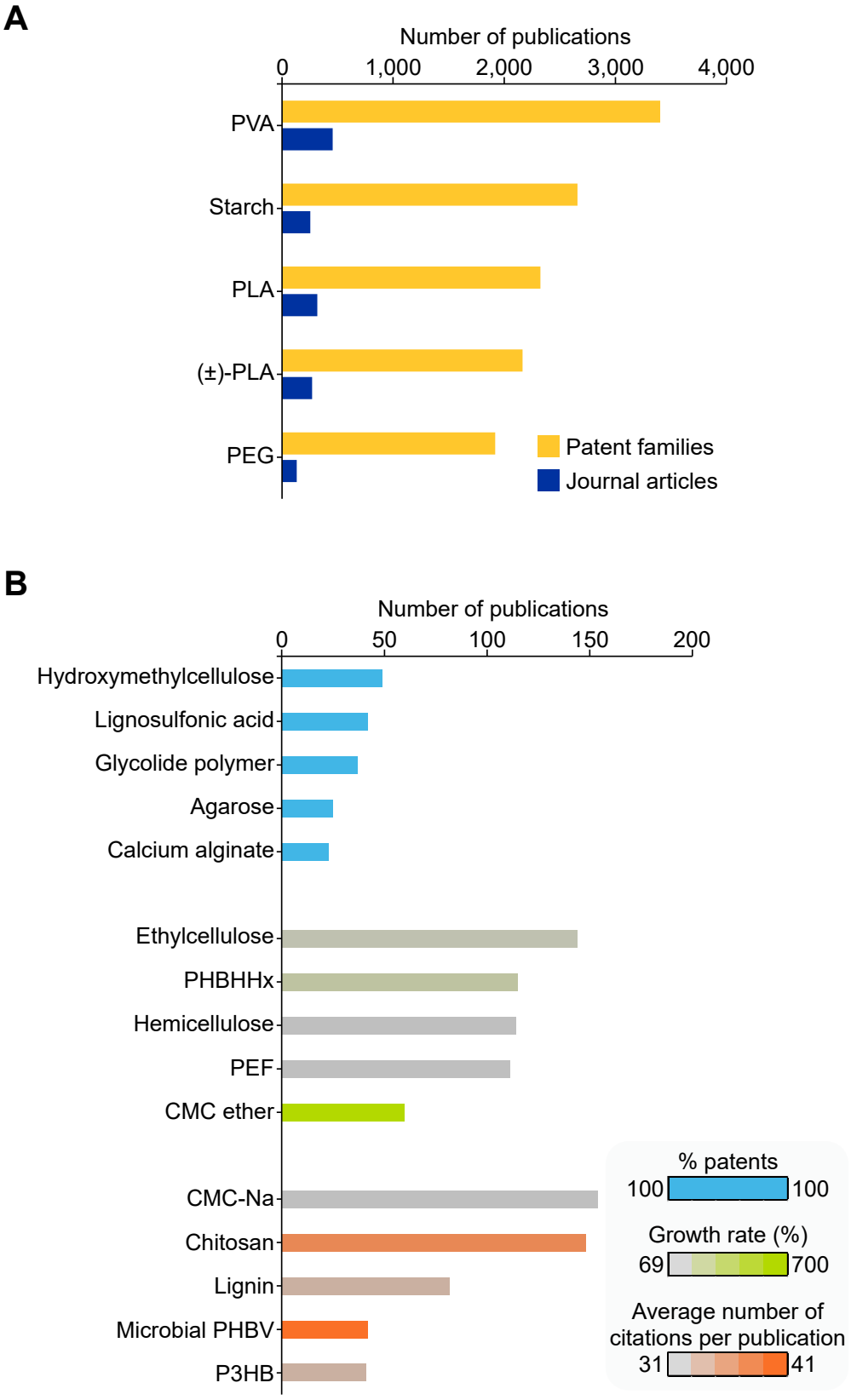


Figure 36. Top 5 sustainable polymer substances in packaging and consumer product applications based on their (**A**) prevalence and (**B**) % of patents, growth (for the period 2020-2024), and average citations per publication. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

applications, where antimicrobial or antioxidant compounds are released gradually to extend product shelf life and maintain quality.[508]

Polymers present in documents with high citations are presented in **Figure 36B**. Chitosan leads with 38 average citations, reflecting its significance as a multifunctional antimicrobial packaging material. Its cationic nature provides broad-spectrum antimicrobial activity while excellent film-forming properties enable development of edible coatings and biodegradable films.[509] Research focuses on optimizing molecular weight and degree of deacetylation for specific barrier properties and antimicrobial efficacy in food packaging applications.[510] Lignin shows 33 average citations, representing bio-based antioxidant packaging systems. As the most abundant aromatic biopolymer, lignin provides natural antioxidant activity through phenolic groups while serving as a renewable alternative to synthetic antioxidants. Research emphasizes lignin modification for improved processability and controlled antioxidant release in active packaging applications, particularly for lipid-containing foods susceptible to oxidative rancidity.[511]

5.3 Synthetic Biology and Biorefineries: Enabling Monomer Supply for Sustainable Polymers

While previous sections identified emerging sustainable polymers through NLP-based growth analysis, understanding their viability requires examining the biological production systems that enable these materials. Synthetic biology represents a transformative technology platform for sustainable polymer manufacturing through two distinct but complementary pathways: fermentative production of renewable monomers that feed into established chemical polymerization processes and direct microbial synthesis of polymers such as PHAs. These biological approaches leverage engineered microorganisms and enzymatic systems to convert biomass feedstocks into either complete polymer chains or discrete chemical building blocks, fundamentally reshaping polymer supply chains from petroleum-based to bio-based origins.

5.3.1.Synthetic Biology Approaches for Drop-in Monomers

In the context of sustainable polymers, synthetic biology functions as an enabling technology that engineers microorganisms and enzymatic systems to convert renewable carbon sources into chemical monomers traditionally derived from petroleum. Unlike direct microbial polymer synthesis such as PHAs, this approach leverages metabolic engineering to produce discrete chemical intermediates that subsequently undergo conventional chemical polymerization. This strategy maintains compatibility with existing polymer processing infrastructure while replacing fossil-based feedstocks with renewable alternatives.

The biorefinery value chain follows a systematic progression: biomass substrates undergo fermentation or enzymatic conversion to yield platform chemicals, which are then purified and polymerized through established chemical routes.[512] Modern biorefineries increasingly integrate multiple conversion pathways, combining fermentation with chemical catalysis to maximize carbon utilization and expand the range of accessible monomers.[513]

The analysis of annual publication data for synthetic biology applications in polymer monomer production reveals significant research momentum in this field (**Figure 37**). Journal publications demonstrate consistent growth from 487 articles in 2015 to 775 in 2024, representing a 59% increase over the decade. This upward trajectory reflects sustained academic interest in metabolic pathway optimization, strain engineering, and bioprocess development for monomer production. The acceleration after 2020, with publications exceeding 600 annually, coincides with increased global focus on circular economy principles and carbon-neutral chemical production.

Patent activity presents a contrasting pattern, remaining relatively stable around 250-450 families annually throughout the study period. The overall distribution shows a 63:37 journal-to-patent ratio, which significantly exceeds typical biotechnology fields where commercial activity often matches or exceeds academic output. This asymmetry suggests that while fundamental research in bio-

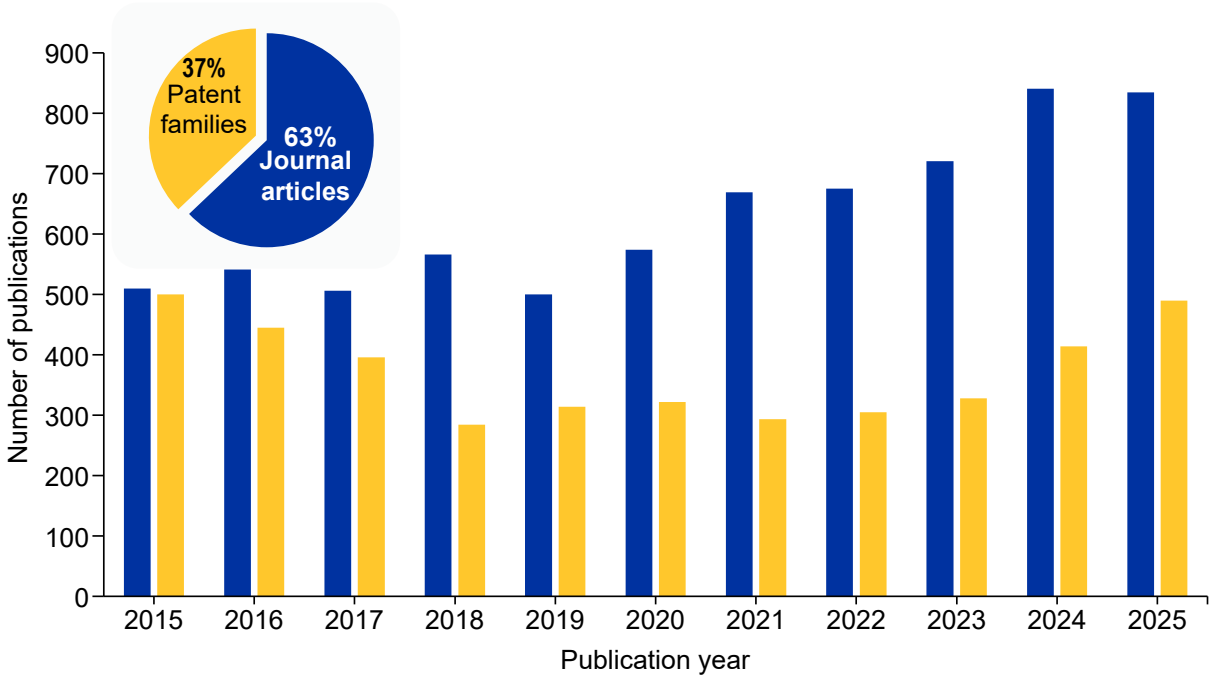


Figure 37. Overall publication trends for select bio-based polymers in synthetic biology related publications. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

based monomer production advances rapidly, commercial translation faces ongoing technical challenges related to production economics, scale-up complexity, and competition with established petrochemical routes.

The publication data, derived from searches within CAS Section 16 (Fermentation and Bioindustrial Biochemistry), encompasses a range of monomers that serve as building blocks for sustainable polymers. These monomers include lactic acid and succinic acid as the two dominant platform chemicals, reflecting their established fermentation pathways and commercial relevance. Adipic acid represents another significant C6 platform for polyamide production. The remaining monomers show more specialized development patterns: 1,3-propanediol for polytrimethylene terephthalate (PTT) production, long-chain dicarboxylic acids (C9-C18) for specialty polyamides, 1,4-butanediol for various polyesters, and 2,5-furandicarboxylic acid for next-generation aromatic polyesters. Diamine monomers include 1,5-pentanediamine, putrescine, and hexamethylenediamine, which pair with dicarboxylic acids to form bio-based polyamides. Additional specialty monomers such as terephthalic acid, 2-pyrrolidone, and related cyclic compounds represent emerging biorefinery targets for high-volume and specialty polymer applications. This focused search within the fermentation and bioindustrial biochemistry domain ensures that the captured publications specifically relate to biological production routes rather than traditional chemical synthesis methods.

The organizational analysis provides insights into the global distribution of synthetic biology capabilities for monomer production (**Figure 38**). Chinese academic institutions lead in publication volume, with Jiangnan University, Nanjing Tech University, and Tsinghua University each contributing over 25 patent families. This concentration reflects China's strategic national investments in industrial biotechnology and bio-based chemical production, supported by funding sources including the National Natural Science Foundation of China, state-level laboratories, and the Knowledge Innovation Program focusing on synthetic biology applications.[514]

European and Asian companies demonstrate strong commercial engagement in this space. Shanghai Cathay Biotech, a specialized industrial biotechnology company, exemplifies the emergence of dedicated biorefinery operators competing alongside both established chemical manufacturers and diversified technology companies expanding into bio-based chemical production.[515] Sinopec has developed extensive capabilities in fermentation-based monomer production, with substantial patent portfolios covering methods for producing long-chain dicarboxylic acids and 1,3-propanediol through microbial fermentation and metabolic engineering.[516-518] DSM (Netherlands) and BASF (Germany) represent traditional chemical companies pivoting toward biotechnology, leveraging their downstream polymer expertise to integrate backward into bio-based monomer production.[519, 520] Japanese companies like Toray Industries have developed comprehensive biotechnology capabilities, with patents covering genetically modified microorganisms for producing adipic acid derivatives (3-hydroxyadipic acid, α-hydromuconic acid) and 1,5-pentanediamine, specifically targeting bio-based routes to polyamide monomers.[521, 522] Samsung Electronics from South Korea has established extensive metabolic engineering capabilities, with over 50 patents covering engineered strains of *Saccharomyces cerevisiae*, *Corynebacterium glutamicum*, and *Escherichia coli* for producing lactic acid, succinic acid, and 1,4-butanediol.[523, 524] These technology

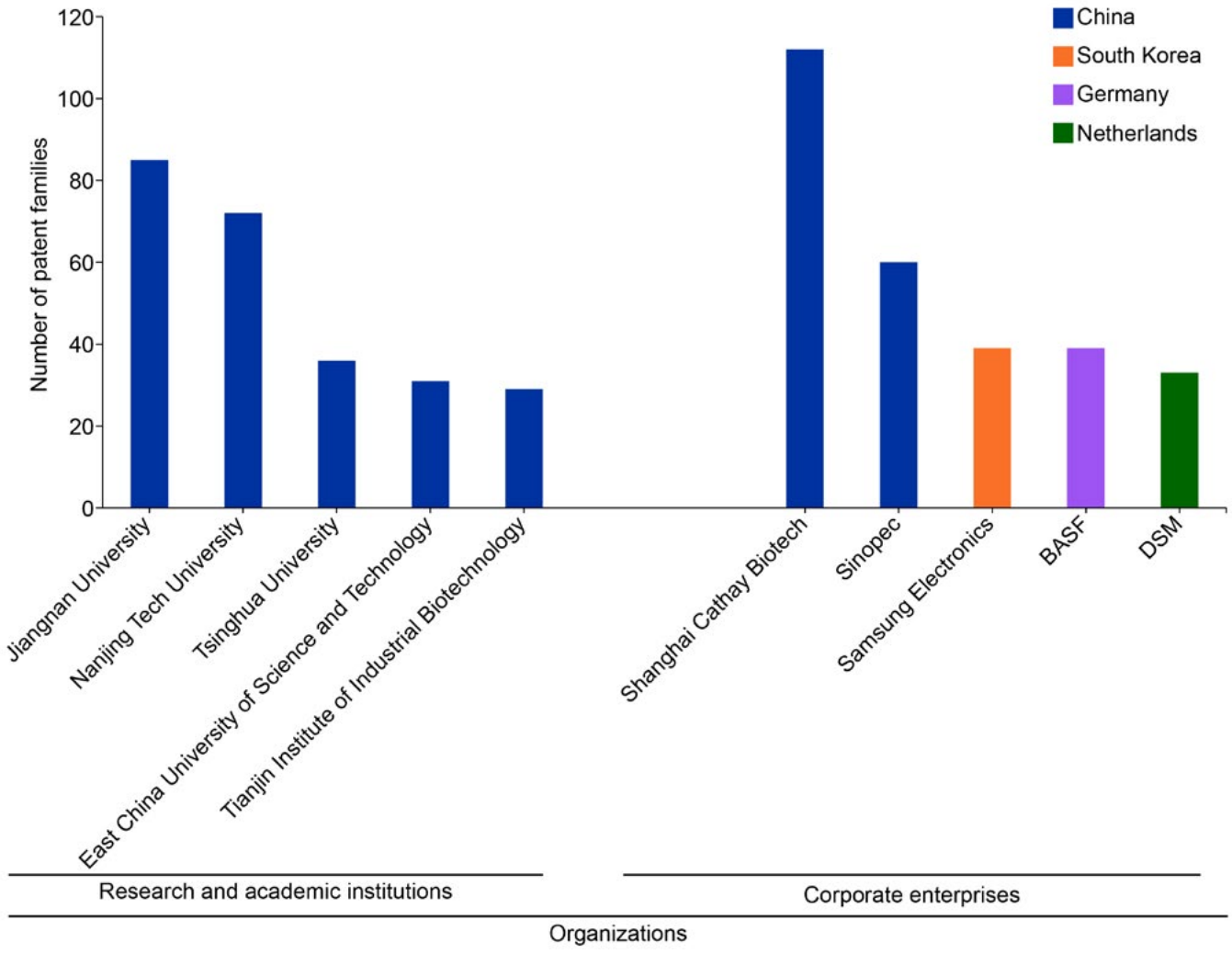


Figure 38. Leading organizations (research and academic institutions and corporate enterprises) in synthetic biology related publications. Data includes patent publications from the CAS Content Collection for the period 2015-2025.

companies' direct investment in strain engineering and bioprocess development indicates a strategic shift toward vertical integration in sustainable material supply chains.

Analysis of monomer-specific publications within CAS Section 16 (Fermentation and Bioindustrial Biochemistry) reveals distinct development priorities aligned with downstream polymer applications (**Figure 39**). Lactic acid represents 58% of journal articles and 45% of patent families in this dataset, establishing it as the primary focus of bio-based monomer research. This concentration directly correlates with PLA emerging as the leading commercial biodegradable polyester in our earlier NLP analysis. The fermentation of lactic acid from various carbohydrate sources has achieved industrial maturity, with multiple commercial plants operating globally.[525]

Succinic acid comprises approximately 20% of both journal and patent publications, serving as a versatile C4 building block for multiple polyester families. Bio-based succinic acid production through bacterial fermentation has progressed from laboratory demonstrations to commercial implementation, with several companies achieving cost-competitive production compared to petroleum-derived alternatives.[526] The polymer applications include PBS, PBSA, and various copolyesters where succinic acid provides biodegradability and flexibility.

The specialized monomers show distinct research patterns reflecting their technological maturity and market potential. 1,3-Propanediol, enables partially bio-based PTT production, with commercial fermentation processes established by DuPont and others.[527] The diol's biological production from glycerol or glucose provides a renewable alternative to petroleum-derived propylene-based routes.

Long-chain α,ω-dicarboxylic acids represent an emerging biorefinery target with significant commercial potential.[528-530] These monomers

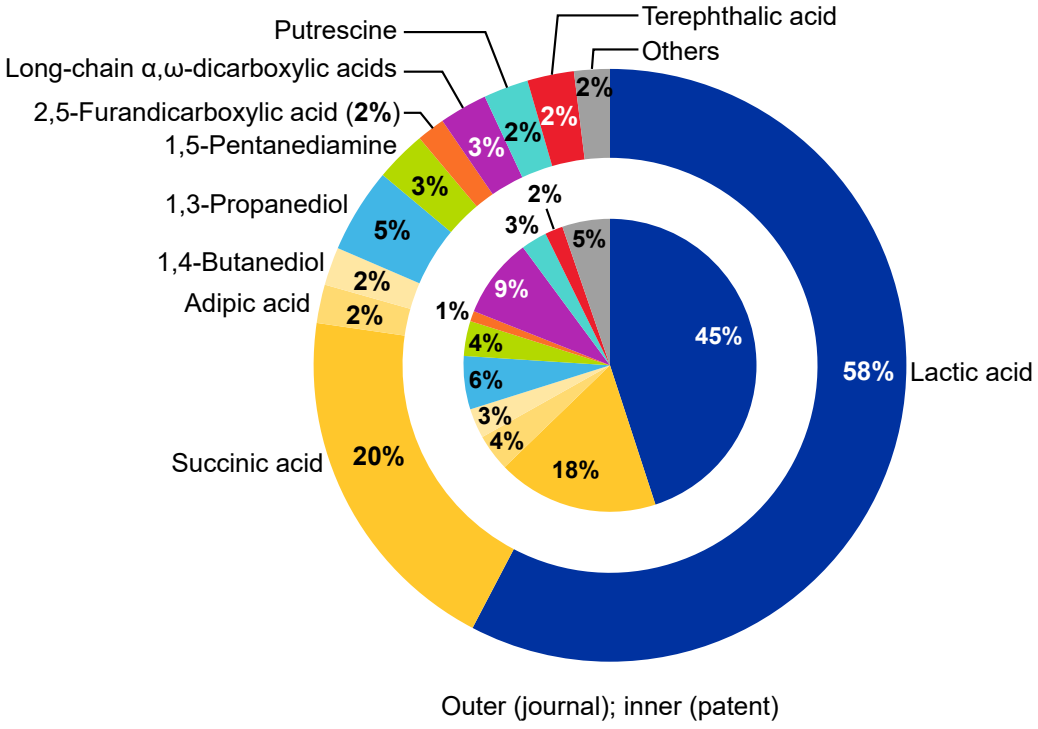


Figure 39. Distribution of bio-based monomer publications showing journal articles (outer ring) and patent families (inner ring) within CAS Section 16 (Fermentation and Bioindustrial Biochemistry). Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

enable production of specialty long-chain polyamides such as PA610, PA1010, and PA1012, which offer superior flexibility, lower moisture absorption, and enhanced chemical resistance compared to conventional short-chain polyamides. Traditionally derived from castor oil or energy-intensive chemical oxidation of petroleum feedstocks, fermentation-based routes promise more sustainable production with better control over carbon chain length distribution. The combination of these long-chain diacids with bio-based diamines creates fully renewable high-performance polyamides for applications ranging from automotive fuel lines to textile fibers.

1,5-Pentanediamine, pairs with adipic acid to form fully bio-based PA56. This novel polyamide demonstrates mechanical properties comparable to PA66 while offering improved moisture management and dyeability for textile applications.[531] The biological production of 1,5-pentanediamine through lysine decarboxylation represents an emerging pathway for bio-based polyamide monomers.[532]

2,5-Furandicarboxylic acid (FDCA) shows the smallest publication share but represents significant future potential as the aromatic building block for PEF. FDCA production from fructose or glucose via 5-hydroxymethylfurfural combines chemical and biological conversion steps, with recent advances improving yield and reducing production costs.[533] PEF offers superior barrier properties compared to PET while being fully bio-based, positioning it as a next-generation packaging material.[534]

1,4-Butanediol serves multiple polymer applications, including PBS, PBAT, and thermoplastic polyurethanes. Bio-based 1,4-butanediol production through direct fermentation from sugars has achieved commercial scale, providing a renewable alternative to traditional acetylene or butane-based routes.[535] Additional specialty monomers receiving biorefinery attention include cyclic intermediates such as 2-pyrrolidone and 2-piperidone, which serve as precursors for nylon-4 and other specialty polyamides offering unique property profiles for medical devices and specialty fibers.[536, 537]

The concentration of research activity around lactic acid and succinic acid platforms reflects a strategic focus on proven fermentation pathways where technical risks are minimized and scale-up knowledge exists. These established platforms provide near-term opportunities for expanding bio-based polymer production. Emerging monomers like FDCA and 1,5-pentanediamine represent longer-term opportunities as metabolic engineering capabilities advance and production costs decrease through technological learning and scale effects.

In conclusion, this tiered development approach, combining optimization of established platforms with exploration of novel pathways, positions synthetic biology as the critical enabler linking renewable carbon sources to the high-performance sustainable polymers demanded by circular economy transitions. Success in this domain requires continued investment in both fundamental research to expand the accessible monomer space and applied development to achieve cost-competitive production at industrial scales. The integration of synthetic biology with chemical catalysis, process intensification, and digital bioprocess optimization will be essential for realizing the full potential of bio-based monomers in sustainable polymer supply chains.

5.3.2. Synthetic Biology Approaches to PHA and Polyester Production

Synthetic biology has also emerged as a powerful platform for the production of PHAs and related polyesters by enabling precise control over microbial metabolism and biocatalytic pathways. Through targeted genetic engineering of native and non-conventional hosts, as well as the integration of enzymatic and hybrid bio-chemical processes, these approaches expand accessible monomer chemistries, improve production efficiency, and facilitate the conversion of renewable or waste-derived feedstocks into sustainable polymer materials.

Recent patent activity underscores genetic and metabolic engineering of microbial hosts as the

primary driver of innovation in PHA production. Multiple disclosures[538-540] focus on engineering canonical PHA-producing organisms to expand monomer diversity, increase intracellular polymer accumulation, and enable tighter control over copolymer composition. By introducing non-native enzymes and optimized gene cassettes, these inventions move beyond conventional PHB and PHBV toward higher-performance copolymers such as P(3HP-co-3HB), reflecting a broader shift from yield-centric optimization toward materials-by-design paradigms in biopolymer synthesis.

In parallel, a distinct innovation pathway leverages non-conventional and extremophilic microbial hosts to address challenges related to scalability, robustness, and contamination control. Archaeal and halophilic production systems enable PHA synthesis under high-salinity or otherwise selective conditions, reducing reliance on stringent sterility while broadening the range of compatible feedstocks.[541, 542] These platforms are particularly attractive for industrial fermentation due to their operational resilience and potential for cost reduction.

Beyond strain engineering, several disclosures emphasize process-level and downstream innovations as critical enablers of commercialization. Approaches targeting broth viscosity reduction, enhanced polymer recovery, and improved post-lysis handling directly address long-standing bottlenecks in PHA purification.[543] These patents highlight the recognition that high fermentation titers alone are insufficient; rather, the integration of biological production with efficient and scalable recovery workflows is essential to achieving cost-competitive bioplastics.

A notable trend across the patent landscape is the growing emphasis on circular and waste-derived feedstocks. Patents describing microbial conversion of polyester waste or non-edible biomass into PHAs point to a convergence between biopolymer synthesis and sustainable materials management.[544] Microbial co-culture systems and waste-to-PHA pathways reposition PHAs not only as biodegradable end products, but also as intermediates within broader circular carbon flows, aligning polymer innovation with sustainability-driven market and regulatory pressures.[545]

Finally, enzyme cascade catalysis, microfluidic reactor integration, and modular bioconversion units reflect increasing cross-pollination between synthetic biology and fine-chemical polymer manufacturing.[546, 547] Collectively, these approaches expand the design space for biologically enabled polymer synthesis, illustrating how biological systems are being used not only to produce PHAs, but also to reshape pathways for conventional polyesters and their precursors.

Collectively, the patents reviewed in this section demonstrate how synthetic biology is reshaping PHA and polyester manufacturing through coordinated advances in strain engineering, host selection, process optimization, and feedstock utilization. The landscape reveals a transition from conventional PHA production toward more versatile, materials-driven platforms capable of generating tailored copolymers, operating under industrially robust conditions, and incorporating renewable or waste-derived carbon sources. Together, these innovations highlight the growing maturity of synthetic biology–enabled polymer technologies and their potential to support scalable, sustainable alternatives to petrochemical-based plastics.

5.4 Summary and Outlook

This comprehensive analysis of sustainable polymers reveals a dynamic field experiencing rapid transformation from niche research to mainstream industrial adoption. The convergence of environmental necessity, technological maturity, and economic viability positions sustainable polymers for transformative impact across multiple industries. The field's trajectory suggests evolution from alternative materials to preferred solutions, with implications for global competitiveness, environmental protection, and technological sovereignty.

6. Polymer Materials for Flexible Electronics

Flexible electronics emerged as a prominent application area of polymers in our NLP analysis, underscoring their expanding technological relevance. Polymers are foundational to the development of flexible electronic systems, enabling devices that combine mechanical deformability with reliable performance. As demand grows for electronic devices that can bend, stretch, fold, or conform, material requirements have become increasingly complex. These systems must not only tolerate extensive mechanical stress but also deliver precise electrical, optical, and chemical functionalities tailored to specific applications.[548]

In this context, polymers and polymer composites serve a wide spectrum of roles across the flexible electronic landscape. They function as non functional structural components, such as substrates, structural support, and insulating layers, where properties like toughness, thermal stability, and ease of processing are essential.[549] Simultaneously, advancements in polymer chemistry have expanded their use into active functional components, including conductive, semiconductive, dielectric, and barrier materials that directly influence device performance. [549] In addition, polymers play critical protective and integration roles, acting as encapsulants, adhesives, and environmental barriers to ensure long term reliability under repeated deformation and diverse operating conditions.[549]

Together, these versatile capabilities position polymers as key enablers of next-generation flexible electronic technologies. This section examines the landscape of polymer materials supporting this evolving field, outlining their functions, performance requirements, and emerging trends in material development.

6.1 Evolving Research Landscape: Publication Trends and Corporate Patent Dynamics

To map the landscape of polymers in flexible electronics, we identified documents relevant to polymer based flexible electronic technologies. These documents include journal and patent publications from 2015 to 2025, with a total volume of ~36 K. The publications cover the use of polymers as flexibility enabling materials, electronic devices that leverage these materials to achieve enhanced flexibility and functionality, and manufacturing processes designed to scale up polymer based flexible materials and device fabrication.

Figure 40 features a pronounced and consistent rise in research and commercial efforts within polymer-based flexible electronics. The pie chart further shows a nearly balanced split between journal articles (52%) and patent families (48%), indicating a well-balanced research and commercial ecosystem.

Building on the global publication trends, the geographic distribution of patent publications offers further insight into where technological leadership in polymer-based flexible electronics is emerging. Accordingly, we examined the patent landscape of corporate enterprises operating in this field. The geographic patent distribution (pie-chart in **Figure 41**) reveals a prominent regional concentration, with China dominating 48% of all patents, followed by Japan at 26%. South Korea contributes 8%, while western organizations show limited presence. The U.S. accounts for 7%, with Germany and France holding 2% and 1%, respectively. This 82% Asia-Pacific concentration has significant implications for global supply chains and technology access, suggesting most fundamental IP in flexible polymer electronics is controlled by Asian companies.

The bar chart in **Figure 41** highlights the top 15 patent organizations (corporate enterprises), revealing how leading chemical and materials companies are positioning themselves to meet the growing demands of the flexible electronics industry. Sumitomo Chemical leads with 245 patent families in polymer formulations and chemical compositions, followed closely by Resonac and Lintec specializing in semiconductor-grade materials and adhesive films, respectively. This concentration among materials suppliers rather than electronics

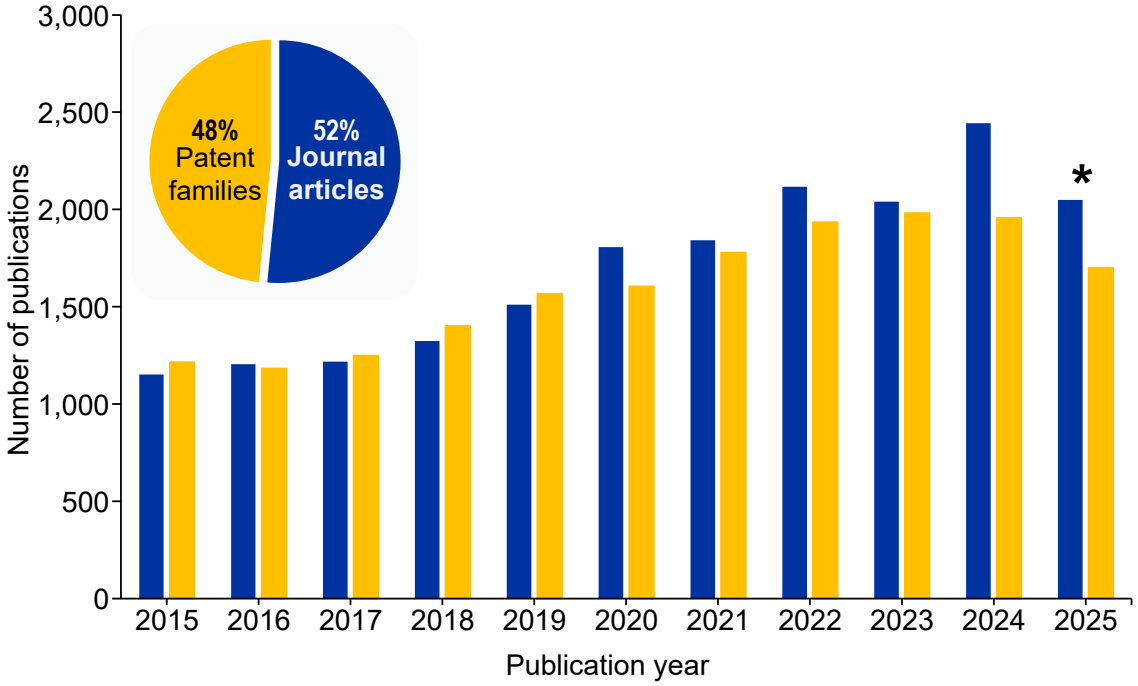


Figure 40. Publication trend of journal articles and patent families in the field of flexible electronics applications with the inset pie chart showing the distribution. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025. *Data only for the months January to November in 2025.

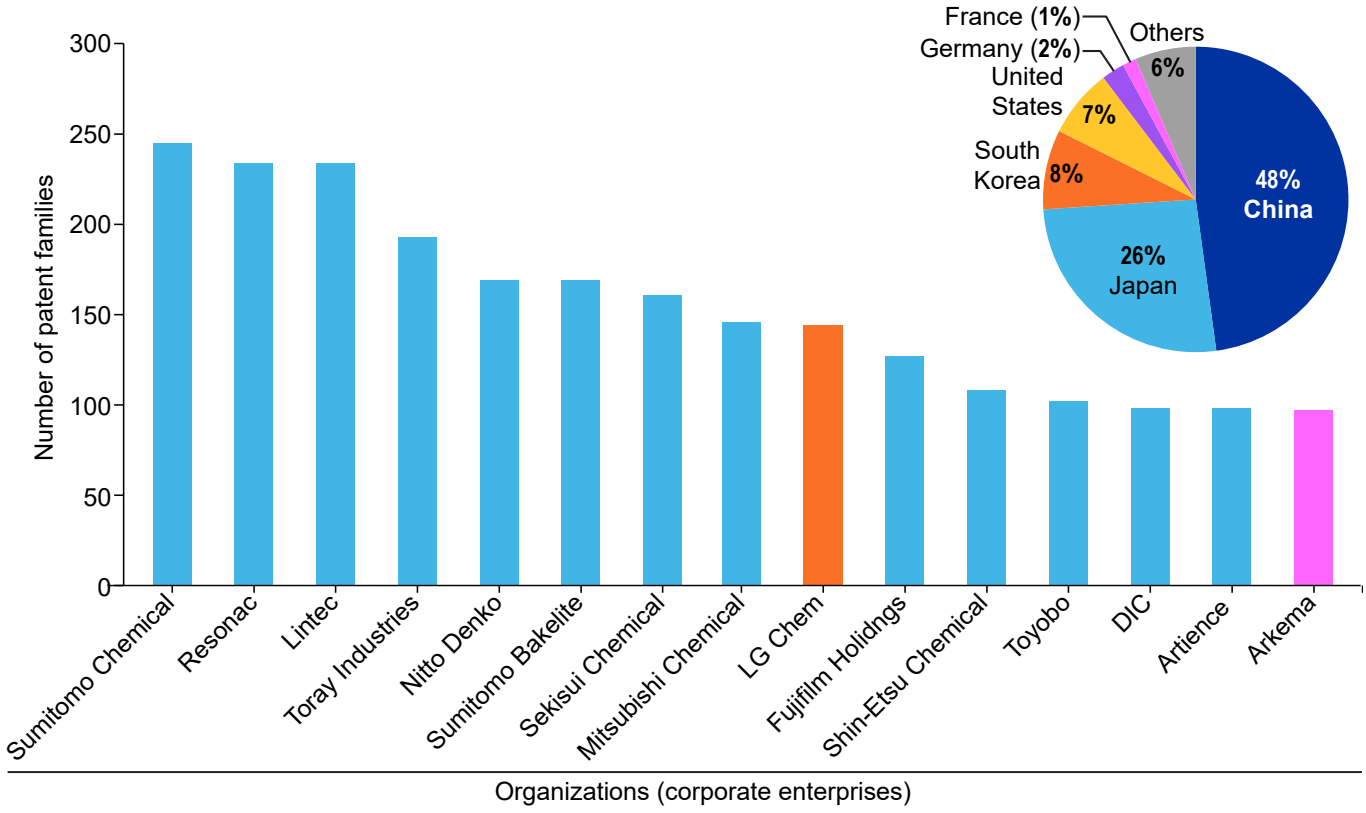


Figure 41. Leading organizations (corporate enterprises) across the patents landscape of polymer-based flexible electronics. The inset pie chart shows the geographical distribution of the organizations. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2025.

manufacturers indicates that fundamental innovation is occurring in the upstream chemical industry. These companies are developing the enabling technologies that electronics manufacturers will later integrate into consumer devices. The technologies behind these innovations cluster into three core pillars of materials that strengthen flexible electronics.

Polyimide and Structural Film Technologies
The flexible electronics materials ecosystem is dominated by polyimide and polyamide-imide film technologies, which define the structural, optical, and thermal backbone of next generation displays. Sumitomo Chemical, Toray Industries, Arkema, Toyobo, and LG Chem lead this segment with films engineered for dimensional stability, low haze, heat resistance, and fold endurance. Their innovations include production of highly imidized polyamide-based film with high surface hardness for front surface plate,[550] wrinkle suppressed polyimide precursor systems,[551] and heat dissipating display substrates.[552] These systems are becoming increasingly multifunctional, combining clarity, mechanical stiffness (young's modulus), dielectric stability, and compatibility with touch, barrier, and adhesive layers within a single polymer architecture.

Bonding and Interface Materials
Bonding, lamination, and process ready interfaces form the second major pillar, driven by adhesive and wet-process chemistries from Lintec, Nitto Denko, Toyobo, Sekisui Chemical, Resonac, and Sumitomo Chemical. These materials govern assembly quality, mechanical reliability, and display uniformity across bending cycles. This includes acrylic copolymer-based adhesives to maintain flexibility at low-temperature[553] as well as heatable high-frequency dielectric adhesive based on thermoplastic resins[554] that enable rapid and low thermal lamination. It also encompasses pressure sensitive acrylic adhesive systems to ensure clean bonding,[555] and circuit level adhesives for electrical precision.[556] Sekisui and Sumitomo Chemical extend this into reworkable, thermally adaptive, and low modulus adhesives, as reflected in patents such as JP6799186 and [557] KR20161001222[558]. Collectively, these innovations illustrate how adhesives have evolved into functional engineering materials from passive bonding layers. A particularly critical subset within this domain is pressure-sensitive adhesive (PSA) technology. Nitto Denko leads in this area with multiple acrylic-based formulations, including inventions featuring reactive emulsifier and water-soluble crosslinking agent to suppress low-temperature pinholes[559] as well as UV-resistant acrylic adhesive layers that enhance durability in optical applications.[560]

Processing and Functional Materials
The final pillar consists of processing, barriers, and functional materials that enable manufacturability, durability, and device operation. Fujifilm Holdings, Shin Etsu Chemical, and Sumitomo Bakelite dominate advanced lithographic and photosensitive chemistries. This includes patents from Fujifilm's flexo and lithography (flexographic printing) platforms[561] and Shin-Etsu's alkali-developable highly functional photosensitive resin system for insulating and protective films.[562] Barrier and encapsulation capabilities which are crucial for organic light-emitting diode (OLED) stability, continue to advance through innovations such as transparent barrier laminates[563] and pressure sensitive block-copolymer adhesive–based lamination process with gas barrier protective sheet.[564] At the functional level, innovations in conductive and sensing materials further expand the design space for deformation tolerant electronics. These include developments such as stretchable conductors[565] and metal nanowire-based touch sensors with polymer substrates and electrodes.[566]

Together, these material categories form a tightly integrated ecosystem where global leaders converge to engineer the optical, mechanical, interfacial, and manufacturing foundations of flexible electronics. With companies shaping the upstream landscape through substrates, adhesives, and functional chemistries, the next question becomes how these polymers operate at a device level. The following section examines the specific roles polymer materials play in enabling structural, functional, and

encapsulation performance in flexible electronic systems.

6.2 Emerging Polymers for Flexible Electronics: From Structural Matrices to Functional Layers and Encapsulants

Flexible electronics innovation is fundamentally driven by advanced polymer materials that provide mechanical flexibility, electrical stability, and processing adaptability required for next generation devices. These polymers enable three core functions within flexible architectures, serving as structural substrates, electronic and dielectric layers, and processing aids through encapsulation and adhesive systems. While the previous section examined the broader patent landscape and highlighted the dominant technologies and organizations shaping flexible electronics from 2015–2025, this section shifts focus to emerging polymer materials gaining prominence in the last five years (2020–2024), as reflected in both journal and patent activity (**Figure 42A** and **42B**).

Figure 42A shows that functional and dielectric polymers dominate the flexible-electronics landscape. Structural polymers form the next largest group, while encapsulant and adhesive polymers make up a smaller but essential share. **Figure 42B** expands on this categorization by mapping specific polymers from journal articles and patent families to their functional roles, illustrating how individual materials contribute to structural, functional, dielectric, and encapsulation applications within flexible electronics.

6.2.1.Structural Polymers – Substrates and Support Systems

Structural polymers serve as mechanical backbones, flexible carriers, and electrically insulating supports that enable bending, shaping, and integration of circuits across flexible, wearable, and deformable devices. Among the polymers observed, most belong to well-established classes used widely in flexible electronics, functioning as substrates, mechanical reinforcements, or insulation layers that support device durability and structural integrity.

Within the journal data, the structural polymers category is populated primarily by bioderived materials such as cellulose, PLA, and chitosan, alongside soft segment candidates including polytetramethylene glycol (PTMG), poly(tetrahydrofuran) (PTHF), and PEG diacrylate. This distribution highlights research emphasis on polymers that offer sustainability, biodegradability, and mechanically adaptable architectures. Recent studies highlight several advances. Cellulose nanofibril are used as biodegradable, printable substrates capable of supporting high resolution conductive patterning.[567] PLA films support low temperature and ITO free OLED fabrication,[568] while PLA derived polyurethanes improve toughness and offer self-healing abilities.[569] PTMG and PTHF-based polyurethane elastomers provide high tensile strength, stretchability, and dynamic-bond-enabled self-healing for stretchable conductors and strain sensors.[570, 571]

Patents, in contrast, focus on PVC, SBS, PVA, TMS PDMS, PVP, PVDF, PCL, and PEVA selected for manufacturability and proven performance. PVC is optimized with stabilizers for thermally stable protective films.[572] SBS appears as a stretchable substrate material in plasma treated elastomeric stacks,[573] while PCL is emerging in biodegradable laminated substrates.[574] PDMS and TMS-PDMS remain foundational for stretchable insulation, supported by patents on fully printed thin film transistor (TFT) systems and three-dimensional (3D) printed circuit architectures.[575, 576] PEVA's role expands through antibacterial and optically clear films.[577, 578] Collectively, this patent activity highlights industry's preference for reliable, scalable chemistry, consisting with academia's push toward greener, degradable, and adaptive structural options.

6.2.2.Functional and Dielectric Polymers – Electronic Performance

Functional and dielectric polymers (**Figure 42B**) form a core materials class in flexible electronics, providing electronic functionality through dielectric stability, conductivity, or specialized processing advantages. The higher share of journal publications (56%)

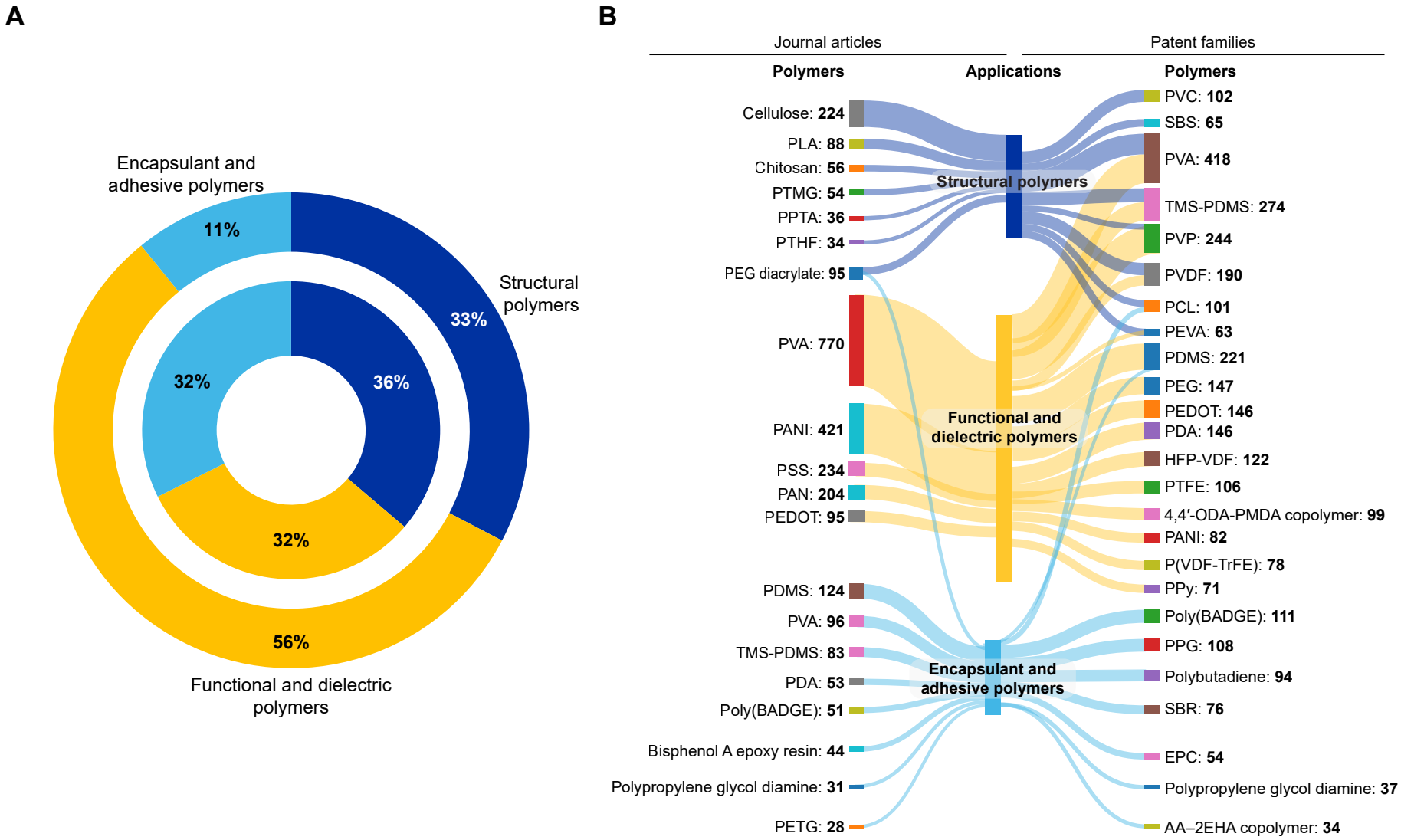


Figure 42. (**A**) Distribution of patent families (inner donut) and journal articles (outer donut) categorized based on the roles of polymers in flexible electronics. (**B**) Sankey diagram of leading emerging polymer substances (based on their growth rate) across three polymer classes – structural, functional and dielectric, and encapsulant and adhesive polymers. Data includes journal articles and patent families from the CAS Content Collection for the period 2020-2024.

compared to patents (32%) likely reflects the field's strong fundamental research focus, where material optimization and structure–property understanding precede large-scale technological commercialization. Within this category, several materials exemplify current research directions. PVA leads due to its dielectric performance and water-soluble processing capability, which enables novel device architectures. Conducting polymers represent another major group. PEDOT continues to show industrial relevance, supported by developments such as photo-patternable and crosslinked high-conductivity formulations.[579] PANI remains relevant through patents on thermally and chemically robust films,[580] while PPy benefits from mature oxidative and electrochemical synthesis routes and remains widely used sensors and energy devices. Recent advances include bioderived flexible substrates incorporating synergistic PPy/PANI conductive networks[581] as well as methods to produce aqueous dispersion of highly conductive PPy.[582]

High-performance elastomers like PDMS and TMS-PDMS demonstrate strong research-to-patent alignment, driven by their low dielectric loss, mechanical compliance and interfacial tunability, particularly in piezoelectric and triboelectric nanogenerators.[583] Fluoropolymers (PVDF, PTFE) also exhibit robust patent activity due to their electroactive properties, flexibility, chemical stability, making them key materials for flexible pressure sensors and nanogenerators.[584]

While established materials dominate the research volumes, emerging polymers within this category signal important future directions for flexible electronics development. Most notably, PDA appears as a cross-functional material with significant presence in both functional and dielectric applications and encapsulant systems, representing a new class of bio-inspired, multifunctional polymers.[585] Additionally, specialty copolymers, e.g., 4,4-oxydianiline pyromellitic dianhydride copolymer (4,4'-ODA-PMDA) play crucial role as high-performance material. Patent evidence further illustrates their relevance-for example, 4,4'-ODA-PMDA copolymers are used as flexible, thermally stable substrates in flexible OLED displays,[586] and they function as robust insulating layers and high-reliability films in microelectronic systems.[587]

6.2.3.Encapsulant and Adhesive Systems – Protection and Assembly

The encapsulant and adhesive polymers category consists of highly specialized systems critical for device protection, assembly, and long-term reliability. Material selection within this category is driven by strict requirements for processing compatibility, cure kinetics, and durability under repeated deformation. The analysis reveals a clear co-existence of materials, notably PDMS, poly(BADGE), polypropylene glycol diamine appears across both journal articles and patent families, indicating strong research-to-industry translation.

On the journal side, acrylic-based (PEG diacrylate) and silicone-based systems (PDMS and TMS-PDMS), which are widely used in optical bonding, film lamination, and reworkable display integration. Innovations in organopolysiloxanes-based PSA formulations demonstrate enhanced mechanical modulus at high-temperature and adhesion to silicone rubbers. These advances align well with the performance requirements of electronics and heat-sealing applications.[559, 588] Acrylic PSAs continue to evolve through high-molecular-weight polyacrylates and acrylic oligomers that offer tunable adhesion, transparency and heat resistance.[589] Overall, these PSA systems are critical enabling materials for foldable OLEDs, flexible touch panels, and thin-film encapsulation technologies. The presence of PDA, along with diverse functional applications, demonstrates growing interest in multifunctional adhesives. Recent studies further highlight this trend, including the development of PDA@PEDOT nanocomposite hydrogels with high adhesion and toughness for strain sensor applications,[590] as well as chemically modified PDA coatings that enable strong structural bonding in thermoplastic-metal hybrid assemblies.[591]

Additionally, established industrial chemistries observed across both sides. On the journal side epoxy systems such as BPA include discussions of encapsulation and structural bonding, reflecting sustained academic interest in optimizing epoxy network mechanics and cure behavior.[592] In contrast, elastomeric modifiers such as polybutadiene and ethylene-propylene copolymer (EPC) appear predominantly on the patent side, where their industrial value lies in enhancing toughness, stress dissipation, and long-term mechanical reliability in flexible device assemblies.[593, 594] These materials perform critical roles in flexible device manufacturing by providing environmental protection against moisture and oxygen, distributing mechanical stress and enabling robust interlayer bonding.

Ultimately, flexible electronics performance depends on the coordinated interaction of substrates, functional and dielectric layers, and encapsulant/adhesive interfaces. Differences in thermal behavior, solvent tolerance, interfacial adhesion, and expansion coefficients mean even high-performing materials can fail when combined. This interdependence explains persistent translation gaps for emerging polymers and the continued patent focus on robust, well-characterized chemistries capable of reliable integration.

6.3 Application-Specific Polymer Distribution

To understand how polymer classes are evolving within the broader flexible-electronics landscape, we analyzed patent publications from 2020–2024 to identify key application areas and emerging material trends. These findings are summarized in **Figure 43**, which presents application-wise patent distribution and highlights polymer growth patterns across categories.

Polymer class specialization patterns and adoption trajectories reflect the field's rapid evolution toward application-specific polymer architectures. Flexible circuits remain the largest application category, with polyamic acids-polyethers and polyamides leading due to their thermal stability, bend endurance, and reliable dielectric performance—qualities essential for multilayer circuit fabrication.[595, 596] Fluoropolymers are used in flexible circuits primarily as high-frequency dielectric layers due to their low dielectric constant and minimal signal loss. They also serve as protective outer films offering excellent chemical resistance, moisture barrier performance, and long-term environmental durability.[597] Acrylic polymers contribute patternability and controlled adhesion for fine-feature lithography, supporting multilayer stacking. Phenoxy resins, while valued for toughness and interlayer adhesion, show more limited expansion. The moderate growth rate of polymers in this category (12-52%) reflects the maturity of flexible circuit manufacturing, where materials such as polyimides already dominate industrial workflows.

In contrast, polymer classes used in display and electroluminescent (EL) devices category show one of the strongest growth (20 to 94%) patterns, indicating advancement in materials used for optical, emissive, and encapsulation layers. Polyurethane-acrylic polymer systems address the classic trade-off between mechanical robustness and optical performance. Polyurethanes provide structural integrity and substrate adhesion, while acrylics contribute high transparency and UV resistance.[598, 599] Polysiloxane–polyether combinations offer a balanced architecture for flexible display materials. Polysiloxanes contribute flexibility, thermal stability, and optical clarity while polyether segments add low-temperature toughness and compliant elasticity, making the system ideal for resilient, high-transparency display layers.[600] Acrylate terminated polyoxyalkylenes systems deliver fast curing, optically clear adhesives/films that maintain compliant elasticity and device compatibility—well suited for flexible OLED packaging and multilayer display bonding.[601]

The wearable electronics segment displays the most dynamic emerging polymer profiles with high growth rates (10-109%). The most rapidly expanding class is fluoropolymers, driven by their exceptional dielectric properties, chemical resistance, and strong performance in triboelectric and piezoelectric devices.[602] Polyurethanes and polyamides follow, supported

by their elasticity, toughness, and compatibility with textile-integrated, stretchable, and skin-contact applications.[603, 604] Polyesters and polythiophenes represent the next tier, showing steady growth due to their dimensional stability, printability, and established use in flexible conductive and semiconducting layers.[605, 606] Across wearables, polymers such as fluoropolymers, polyesters, polyoxyalkylenes, polyimides, polysiloxanes, acrylic polymers, and polythiophenes dominate because they combine biocompatibility, stretchability, low temperature processing compatibility. Their rising adoption reflects rapid expansion in health monitoring, soft robotics, smart textiles, and e-skin. Nanogenerators-based wearables represent a notable subset, relying heavily on fluoropolymers (e.g. PVDF, PTFE) and polyesters for their intrinsic triboelectric and piezoelectric performance, along with elastomeric polysiloxanes and thermally stable polyimides.[607] The strong growth of fluoropolymer-based nanogenerator materials aligns with rising interest in self-powered wearable systems.

Sensors span applications in industrial strain mapping, environmental and chemical sensing, tactile robotic interfaces, and biomedical monitoring, resulting in a wide variability in polymer growth rates. Across this category emerging polymer class growth rate ranges from 10–74% as the category must accommodate diverse transduction mechanism. Polyoxyalkylenes lead (~74%) due to their low glass transition temperature (Tg), ether rich backbones that form soft, permeable networks ideal for strain, ionic, and biochemical sensing.[608, 609] Fluoropolymers follow, as low dielectric constant (k), low loss dielectrics for capacitive, piezoelectric, and high frequency sensors. Polyimides and polysiloxanes occupy the next tier — polyimides offering thermal and dielectric stability for harsh environment sensing, and polysiloxanes providing elasticity and biocompatibility for skin mounted devices. Polyesters show moderate growth due to their dimensional stability and printability. Overall, the fastest growing sensor materials are those enabling tunable polarity, softness, and dielectric behavior.

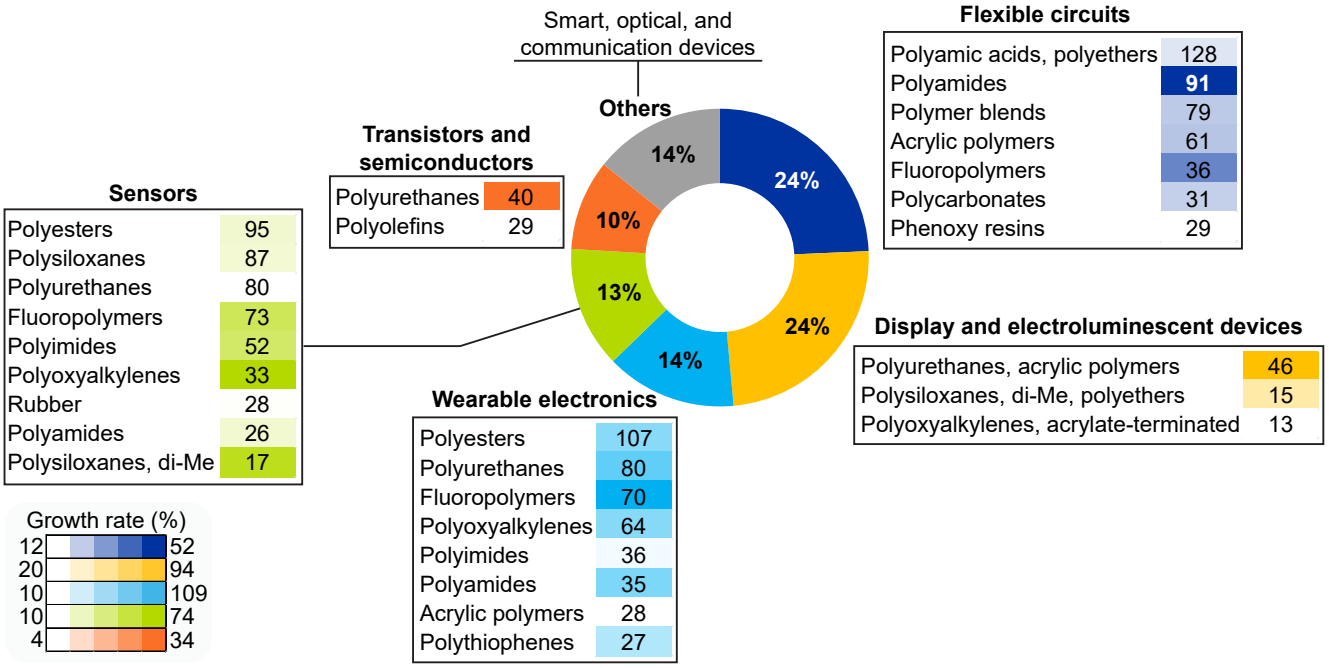


Figure 43. Emerging flexible electronics applications across the polymer landscape (donut chart). The heat map represents the emerging polymer class distribution, color coded based on their growth rate. Data includes patent publications from the CAS Content Collection for the period 2020-2024.

In the transistor and semiconductor applications, growth remains limited (4–34%) as the field relies on matured conjugated semiconductors (polythiophenes), and established dielectric materials (polyimides, fluorinated dielectrics). These systems have long-optimized electronic structure, morphology, and interface energetics supporting mobility, stability, and fabrication compatibility. Only polyurethanes and polyolefins show notable emergence: polyurethanes, which offer mechanically adaptive segmented architectures that support flexible encapsulation and stress mitigation; and polyolefins, whose chemically inert, low-k hydrocarbon backbones support simple insulating and passivation roles.[610] The "Others" category (14%) includes smart, optical and communication devices, where materials growth tied to niche functional demands.

Across the landscape, the fastest-growing polymer classes—polysiloxanes, polyurethanes, polyesters, fluoropolymers, polyoxyalkylenes, and polythiophenes—are those enabling stretchability, skin conformity, lightweight wearable design, and organic semiconducting performance. In contrast, mature systems such as polyimides and polyamides show lower growth, consistent with their established roles in flexible circuits and display manufacturing. These patterns indicate that expansion in flexible electronics is increasingly concentrated in materials supporting next-generation wearable, stretchable, and self-powered platforms. To complement this category-level landscape of emerging technologies, the following subsections provide a deeper analysis (for 2015-2024) at the level of prominent polymer substances.

6.3.1.Flexible Circuits

This application includes flexible and printable circuits, relying on polymer substrates and polymer based inks to enable additive manufacturing and printing processes. In these systems, polymers provide mechanical flexibility, printability, and conductive/dielectric properties essential for next generation circuit design. **Figure 44** shows the distribution of top polymer substances across journal and patent publications. A comparison of these datasets reveals clear differences between materials dominating exploratory research and those that have achieved industrial maturity.

Polyesters exhibit a pattern characteristic of a mature commercial platform: moderate research and strong patent representation. PET is widely used in flexible displays, printed photovoltaics, and thin-film electronic circuits due to its strength and optical properties. Current innovation focuses predominantly on improving surface uniformity, dimensional stability, barrier layers, and lithographic compatibility.[611, 612] Polysiloxane-based polymers, including PDMS and TMS-PDMS, show balanced journal and patent activity. These polymers are foundational in flexible electronics because of their mechanical flexibility, optical transparency, biocompatibility, and compatibility with soft lithography processing.[613]

Vinyl polymers, particularly PVA, show strong journal activity due to their role as a water-soluble substrate or sacrificial layer in transfer printed and 3D integrated electronics. This aligns with studies highlighting water-soluble PVA films as effective support for conformal and transient electronics.[614] However, PVA shows only moderate patent activity, compared to PET reflecting known industrial constraints such as moisture sensitivity and limited long-term stability. PSS appears in both journal and patent, reflecting its role as a widely used ionic/conductive additive in printed electronics.[615] PVP and poly(acrylic acid) appear mainly in patents as supporting functional layers for surface modification, dispersion, and interface engineering.[616, 617]

On the functional materials side, conductive polymers such as PEDOT (often PEDOT:PSS and PANI[618] appear primarily in patent filings. These systems are central to printed conductor development, with ongoing efforts aimed at improving conductivity, environmental stability, and solution processability, reflecting their intermediate technology readiness and active materials evolution.

Natural polymers, including cellulose and chitosan, show balanced journal–patent activity, driven by interest in bioderived, biodegradable polymers for sustainable electronics. While cellulose is not intrinsically conductive, it serves as a biodegradable base[567, 619] or structural matrix and becomes electrically functional when integrated with fillers such as carbon nanotubes, graphene or metal nanowires.[620] These materials are well-positioned for disposable or eco-designed devices but are not yet replacements for high-performance functional polymers.

Collectively, these journal–patent activity patterns illustrate that flexible and printable electronics rely on polymer systems across a broad spectrum. From commercially entrenched substrates (e.g., polysiloxanes, polyesters) to research intensive functional materials (conductive polymers, vinyl polymers) and emerging bioderived alternatives. This distribution provides guidance for strategic material selection and R&D investment in next-generation flexible electronic technologies.

6.3.2.Display and Electroluminescent devices

In displays and EL devices, polymer selection is strongly constrained by optical, mechanical, and processing requirements across multilayer stack architectures. As a result, industrial innovation centers on established polymers, such as polyesters, polyimide, and polyamide-imides (PAI), where companies such as Sumitomo Chemical, Toray Industries, Arkema, Toyobo, and LG Chem focus on incremental improvements rather than introducing new classes of materials (as discussed in **Figure 41**). Advances emphasize imidization control, surface hardness, wrinkle suppression, and thermal dissipation, reflecting the need for substrates that remain stable under thermal cycling and mechanical strain.[550-552] This maturity aligns with the patent landscape, where commercially entrenched polymers (PET, polyimide) dominate filings, while emerging mixed ionic-electric conductive systems such as PEDOT:PSS exhibit high research activity but limited commercial translation.

Figure 45 shows the substance distribution across journal and patent publications. Polyesters

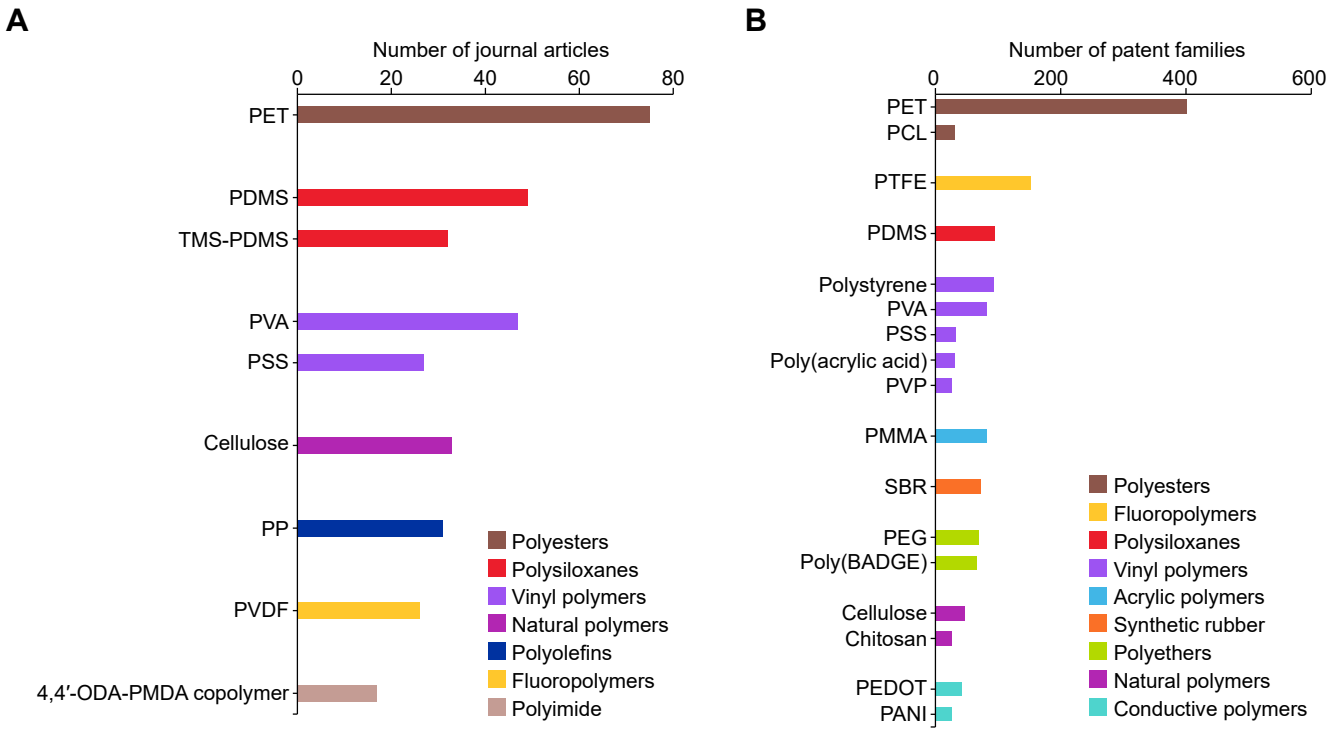


Figure 44. Polymer substance distribution across (**A**) journal articles and (**B**) patent families for flexible circuits in the polymers dataset. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2024.

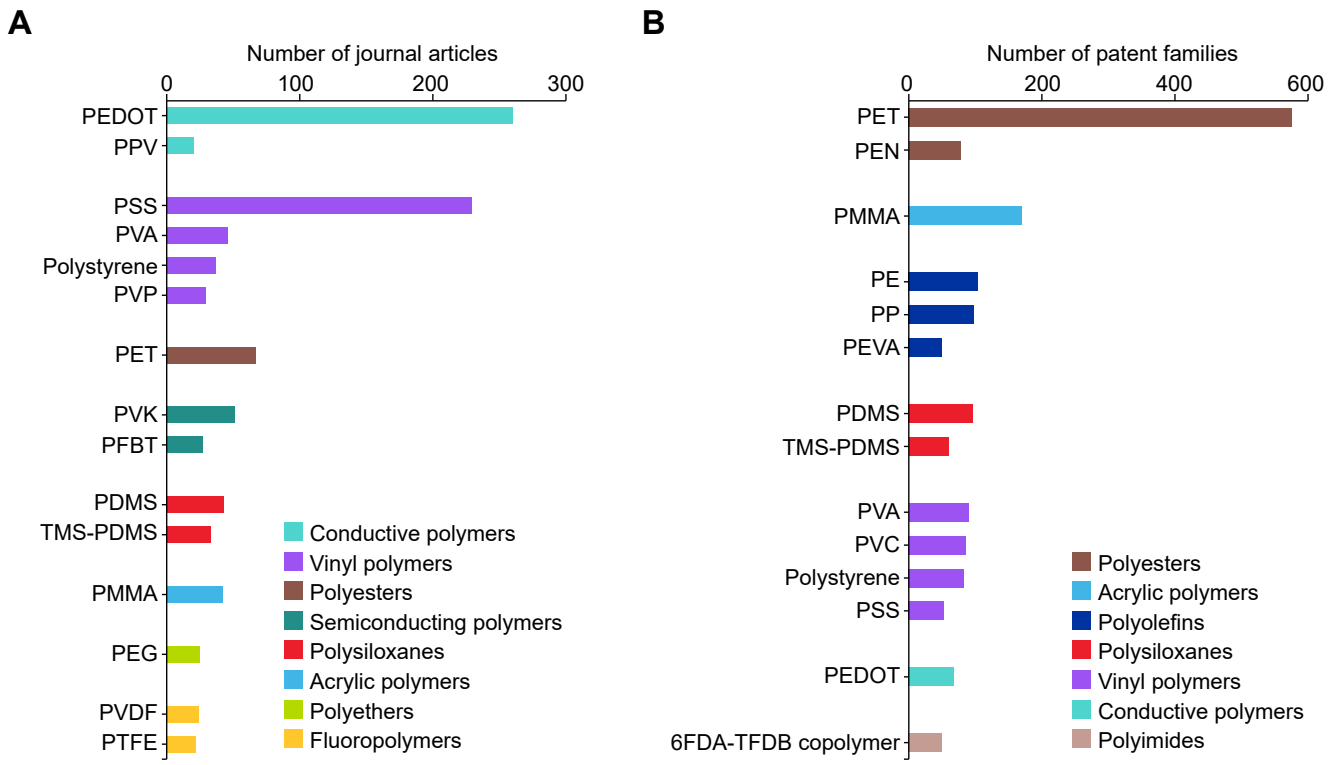


Figure 45. Polymer substance distribution across (**A**) journal articles and (**B**) patent families for display and electroluminescent applications in the polymers dataset. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2024.

especially PET dominate the patent landscape, reflecting their long-established role as reliable substrates in display and EL manufacturing. PET offers excellent dimensional stability, optical clarity, and processing compatibility with roll-to-roll and multilayer device construction. Recent developments demonstrate continued development, such as Ag loaded PET films for enhanced barrier performance,[621] lightweight PET-aerogel composites with crack-resistant structures,[622] and biodegradable PET copolyester variants.[623] These innovations reinforce PET's status as a technologically mature, industry-aligned substrate.

Conductive polymers show distinct research–patent contrasts. PEDOT and poly(p-phenylenevinylene) (PPV) appear strongly in journal publications but have low patent volumes (PEDOT), indicating they remain primarily research-driven materials within display and EL applications. Semiconducting polymers such as poly(N-vinylcarbazole) (PVK), poly(9,9-dioctylfluorene-alt-benzothiadiazole) (PFBT), exhibit strong academic activity. These materials serve primarily as hole-transport layers, emissive matrices, and ionic conductors,[624] attracting interest due to tunable electronic structures and solution processability. However, their instability under operational stress, limited device lifetimes, and challenges in large-area uniformity hinder widespread industrial integration.

Polymers such as PVA, PMMA, polystyrene, PDMS, and TMS-PDMS exhibit balanced research and patent activity. These materials function as dielectric layers, optical smoothing layers, encapsulation films, flexible waveguide or patterning media. Academic interest continues as refractive index control, surface roughness, and adhesion remain critical to OLED efficiency and stability. Their steady patenting activity suggests ongoing for optimization printability, optical quality, interfacial control, and compatibility with roll-to-roll and flexible processing.[625]

At the patent-dominant end of the spectrum are polymers such as poly(ethylene naphthalenedicarboxylate) (PEN), PE, PP, PVC, PEVA, and PTFE. These materials serve as structural substrates, barrier layers, and support films in commercial display manufacturing.[626, 627] Their patent intensity reflects deep integration into industrial workflows and ongoing improvements around moisture barriers, thermo-mechanical stability, lamination reliability, and multilayer composite construction.

Finally, polymers such as 6FDA–TFDB copolymer show a patent leaning profile with focused research engagement. Their roles in transparent high-Tg substrates, foldable device cover films, and ferroelectric dielectrics position them as enabling materials for next generation display formats.[628, 629] Their patent visibility indicates competitive industrial investment, particularly in transparent polyimide formulations, while ongoing research continues to refine optical clarity, thermal resistance, and deformation resistance for flexible and curved displays.

6.3.3.Wearable Electronics

Wearable electronics, including wearable sensors, e-skin, body-integrated devices, and wearable nanogenerators, represent the most biocompatibility-demanding segment of flexible electronics. Polymer selection in this category is driven by the need to maintain safe, comfortable and stable contact with the body while maintaining electronic functionality. **Figure 46** illustrates the broad distribution of polymer classes in these applications, reflecting the field's emphasis on solving fundamental bio-integration challenges. Material innovation in this space is focused around achieving tissue-like mechanical properties, biocompatible interfaces, and reliable performance during continuous body contact.

Vinyl polymers continue to dominate both journal and patent publications in bio-integrated soft electronics due to their tunable chemistry, mechanical softness, and compatibility with hydrogel engineering. PVA leads academic activity due to its ability to form biocompatible, ionically conductive hydrogels with tissue-like mechanical properties, supporting ECG/EMG monitoring and skin-interfacing sensors.[630] PVA and acrylamide-N,N-methylenebisacrylamide copolymer (acrylamide-MBAA) networks provide self-healing behavior, adhesion and hydration stability necessary for conformal e-skin applications.[631, 632] Additionally, PAM, PSS used along with PVA and PEDOT in producing double network hydrogels.[633] These systems represent emerging bio-integrated architectures designed to match skin mechanics and maintain reliable electrical contact during motion.

Conductive polymers, PEDOT, PANI, and PPy, show balanced journal-patent activity, indicating successful translation from laboratory to commercial devices. These π-conjugated polymers maintain conductivity under mechanical deformation essential for physiological monitoring. PEDOT is particularly delivering mixed ionic-electronic transport particularly suited for biological interfaces.[634] The presence of PSS as a polyelectrolyte dopant creates the mixed conduction mechanisms necessary for bridging electronic devices with ionic biological systems, enabling stretch-tolerant electrodes and sensing films that can accommodate the dynamic mechanical environment of body-worn applications.[635]

Elastomeric polysiloxanes, especially PDMS and TMS-PDMS, dominate patents while maintaining research attention. Their Si–O–Si backbone provides ultra-low modulus, stretchability, chemical inertness, and thermal stability, enabling long-term comfort and mechanical compliance. PDMS-based systems function as soft encapsulants, sweat-resistant protective layers, and stretchable matrices for conductive interconnects across wearable sensors, e-skin, and energy harvesting devices.[636, 637] Fluoropolymers enable critical energy harvesting functionality in wearable devices. PVDF and PTFE show strong patent activity, indicating successful translation from fundamental research to commercial nanogenerators. PVDF remains the primary piezoelectric polymer, with efforts focused on enhancing properties through nanofillers, copolymerization, and processing optimization, as seen in PVDF/MXene

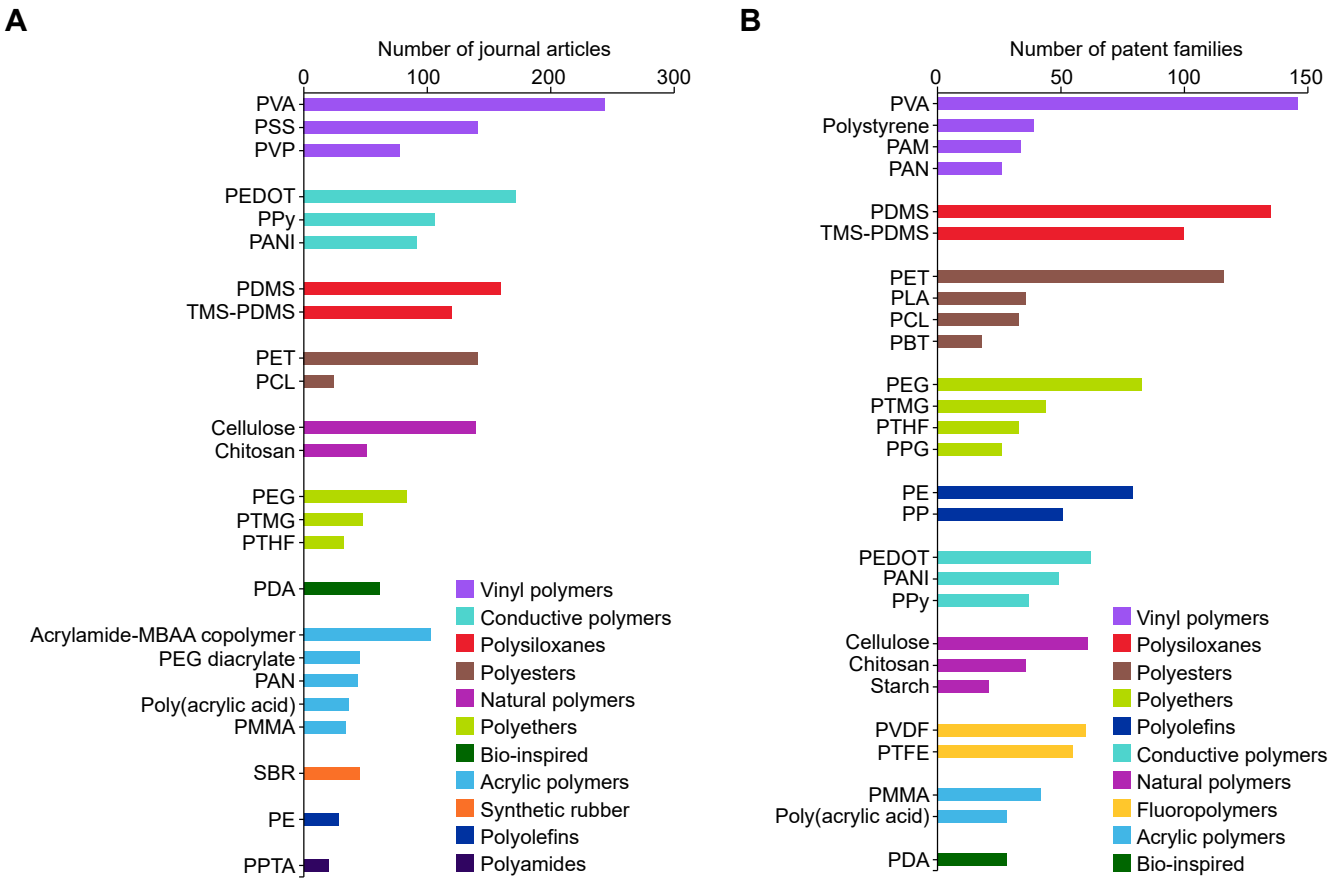


Figure 46. Polymer substance distribution across (**A**) journal articles and (**B**) patent families for wearable electronics applications in the polymers dataset. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2024.

nanofibers[638] and graphene-reinforced PVDF membranes.[639] PTFE's highly negative triboelectric polarity and durability support long-term charge generation, demonstrated in nanotextured PTFE-SiO_2 nanofibers and cryogenic-resilient PTFE textile triboelectric nanogenerators (TENGs).[640]

Across wearable electronics, the preferred materials are those that combine softness, biocompatibility, stretchability, and conformal contact with stable electrical performance. Materials are selected for their ability to match skin-level mechanics, maintain comfort during continuous body movement, and provide low-impedance interfaces with biological tissues. Systems that offer ionic or mixed conduction, self-adhesion, moisture tolerance, and long-term durability under repeated deformation show the strongest research momentum. On the industrial side, materials with consistent mechanical compliance, environmental stability, and compatibility with scalable fabrication dominate patent activity. Overall, wearable electronics prioritize polymers that can reliably interface with the human body—balancing mechanical softness, biocompatibility, and robustness—while supporting sensing, energy harvesting, or communication functions in deformable form factors.

6.3.4. Sensors

As sensing demands expand from simple mechanical strain detection to biochemical and environmental monitoring, flexible sensor development increasingly relies on polymer chemistries that can be tuned for flexibility, conductivity, stability, and selective analyte response. **Figure 47** maps major polymer classes and their substances driving this field between 2015–2024, highlighting a split between research-intensive responsive materials and commercially mature ones.

The analysis in **Figure 47A** and **47B** shows strong overall growth of vinyl polymers (PVA, PVP) leading academic publications with moderate patent activity. PVA's research dominance stems from its hydrogel behavior suitable for humidity, pH, and biosensing applications.[641] PVP also shows notable research presence, while vinyl polymers such as PSS and PVC[642] appear in patents, reflecting roles in ion-conducting layers and encapsulation.

Polysiloxanes (PDMS and TMS-PDMS) dominate the patent publications in this spacefield. Their dominance underscores their established role as preferred substrates for microfluidic and flexible sensors due to their optical transparency, gas permeability, and ease of fabrication.[643] Significant research investment is also seen in conducting polymers, particularly PEDOT and PPy. Together with PANI, PEDOT and PPy also show balanced activity in patents, indicating successful translation of conductive polymers from laboratory demonstrations to commercial sensing elements, especially in electrochemical and gas sensors.[644, 645]

Acrylamide–MBAA copolymers and poly(acrylic acid) show notable research activity, indicating a growing focus on stimuli-responsive materials capable of measurable property changes upon analyte exposure. These polymers contribute to the development of adaptive, responsive sensing architectures[646, 647] as well as strain sensors.[648] PET shows strong growth in both journal and patent publications, reflecting its role as a stable and reliable substrate in commercial sensor systems.[649]

PVDF and PTFE appear across both research and patents, linked to performance needs in flexible sensors. PVDF provides strong piezoelectric response and mechanical flexibility for efficient signal generation,[650] while PTFE offers exceptional chemical inertness and thermal stability, ensuring reliable sensing in harsh or variable environments.[651] Their presence aligns with applications requiring piezoelectric or chemically inert materials in various sensing environments.

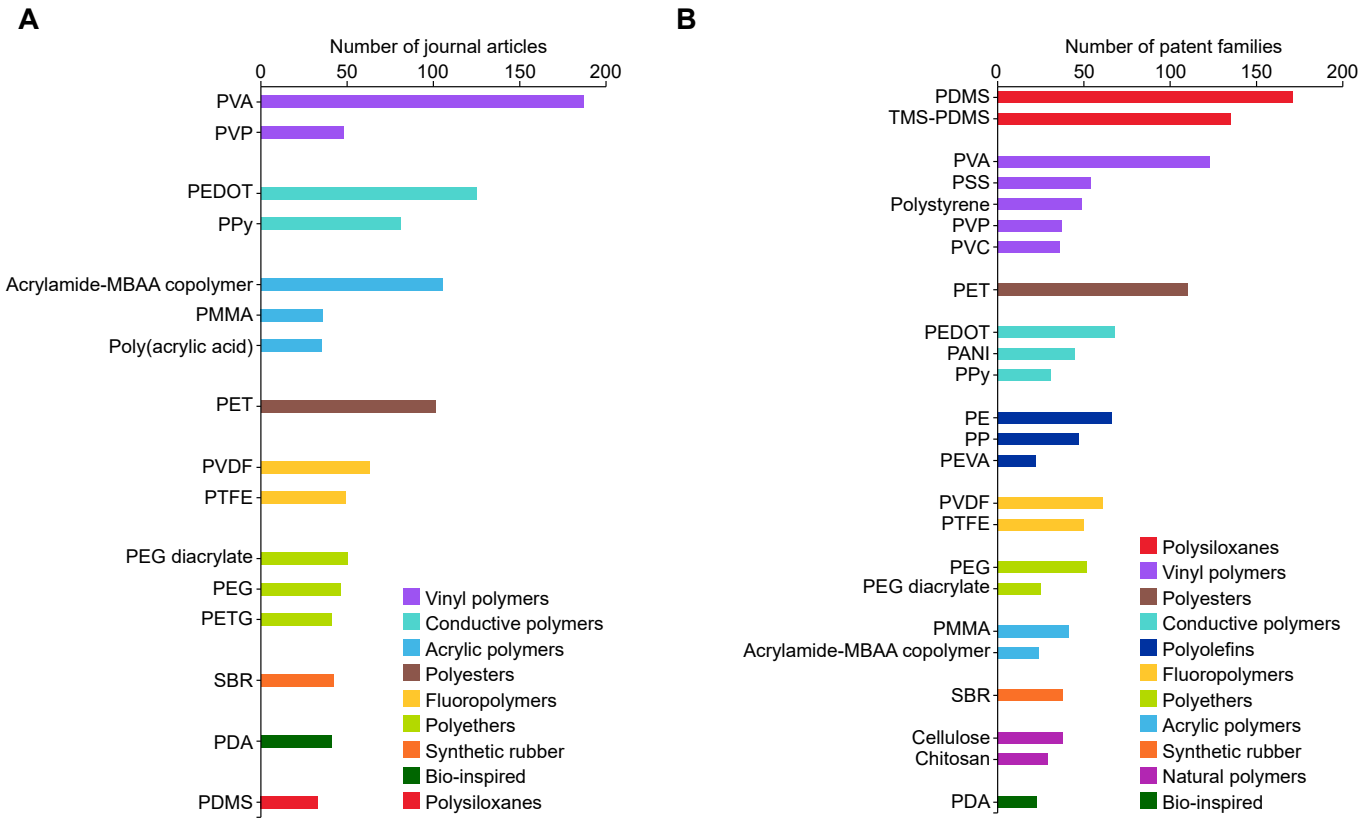


Figure 47. Polymer substance distribution across (**A**) journal articles and (**B**) patent families for sensors in the polymers dataset. Data includes journal and patent publications from the CAS Content Collection for the period 2015-2024.

The presence of cellulose and chitosan highlights the field's movement toward sustainable and implantable sensor technologies, indicating that next-generation sensors must simultaneously achieve high performance while meeting increasingly stringent biocompatibility and environmental sustainability requirements.[652, 653]

Overall, the sensor landscape shows that materials with cross-application versatility—rather than narrow device specialization—are the most successful. Polymers such as PDMS, PVDF, PVA, and PEDOT exemplify this trend by combining multiple essential functions: mechanical compliance, energy-harvesting capability, biocompatible sensing behavior, and reliable conductivity. Journal–patent patterns reveal that while established technologies depend on mature high-performance polymers, rapid growth is driven by materials that simultaneously deliver flexibility, biocompatibility, electronic responsiveness, and environmental stability within a single architecture. This convergence signals a shift toward integrated polymer systems, where future advances will hinge on chemistries capable of adapting across diverse sensing demands—from soft, skin-like interfaces to mechanically robust environmental sensors—while maintaining specialized performance attributes required for each application.

6.4 Emerging Manufacturing Processes and Scale-Up Pathways

In this analysis, we examined the emerging processing routes that shape and functionalize polymers for flexible electronics. Within the polymer-based flexible electronics patent landscape, we identified documents that highlight developments in manufacturing strategies and scalable production processes for flexible polymeric materials. Patent activity from 2020–2024 (**Figure 48**) underscores how advancements in bulk forming, coating, and structured fabrication are redefining manufacturing pathways for polymer-based flexible electronics.

Bulk-forming and shape-forming processes enable polymers to be cast, molded, or patterned into thin, compliant geometries, allowing materials to retain their intrinsic softness and elasticity. This includes processes such as extrusion, hot-press molding, thermoforming, and calendaring, which are essential for producing large area films, sheets, and molded substrates that support flexible devices. Their prevalence reflects the stability and scalability of polymers with reliable melt behavior and high-throughput compatibility. PVA with high growth (~69%) leads this area due to excellent film forming ability, smooth melt processing, and compatibility with large-area extrusion and calendaring.[654] Acrylonitrile-butadiene-styrene copolymer (ABS) follows based on its high melt strength, impact resistance, and dimensional stability,[655] allowing it to be extruded or thermoformed into robust housing and support frames for flexible modules. PBAT and ethylene–1–octene copolymers show moderate growth, offering clean melt processing, tunable stiffness, elasticity, for bend-tolerant sheets and conformable insulators.[656, 657] PBT provides semi crystalline durability for mechanically stressed substrates, while PLA and bio polyesters gain traction as sustainable, melt-processable alternatives. Together, these materials with predictable melt rheology, flex-resistant structural integrity, and sustainability potential, continue driving bulk-forming adoption.

Thin-layer and film-formation processes convert polymers into ultrathin, lightweight, and highly compliant formats that preserve flexibility, enabling them to bend, stretch, and conform to curved surfaces without mechanical failure. These processes show substantial growth of polymers (15–89%) as they deliver uniform dielectric, conductive, optical, and barrier coatings. PMMA and PSS are emerging due to their controlled solubility, excellent film formation, and smooth morphologies ideal for gate dielectrics, interlayers, and charge modulating coatings.[658] PEDOT remains the dominant solution-processed conductor due to its versatile compatibility with spin and blade deposition, making it the default electrode and sensor interface material across printed and hybrid platforms. PVA and PEG appear in niche roles: PVA and PEG appear in specialized

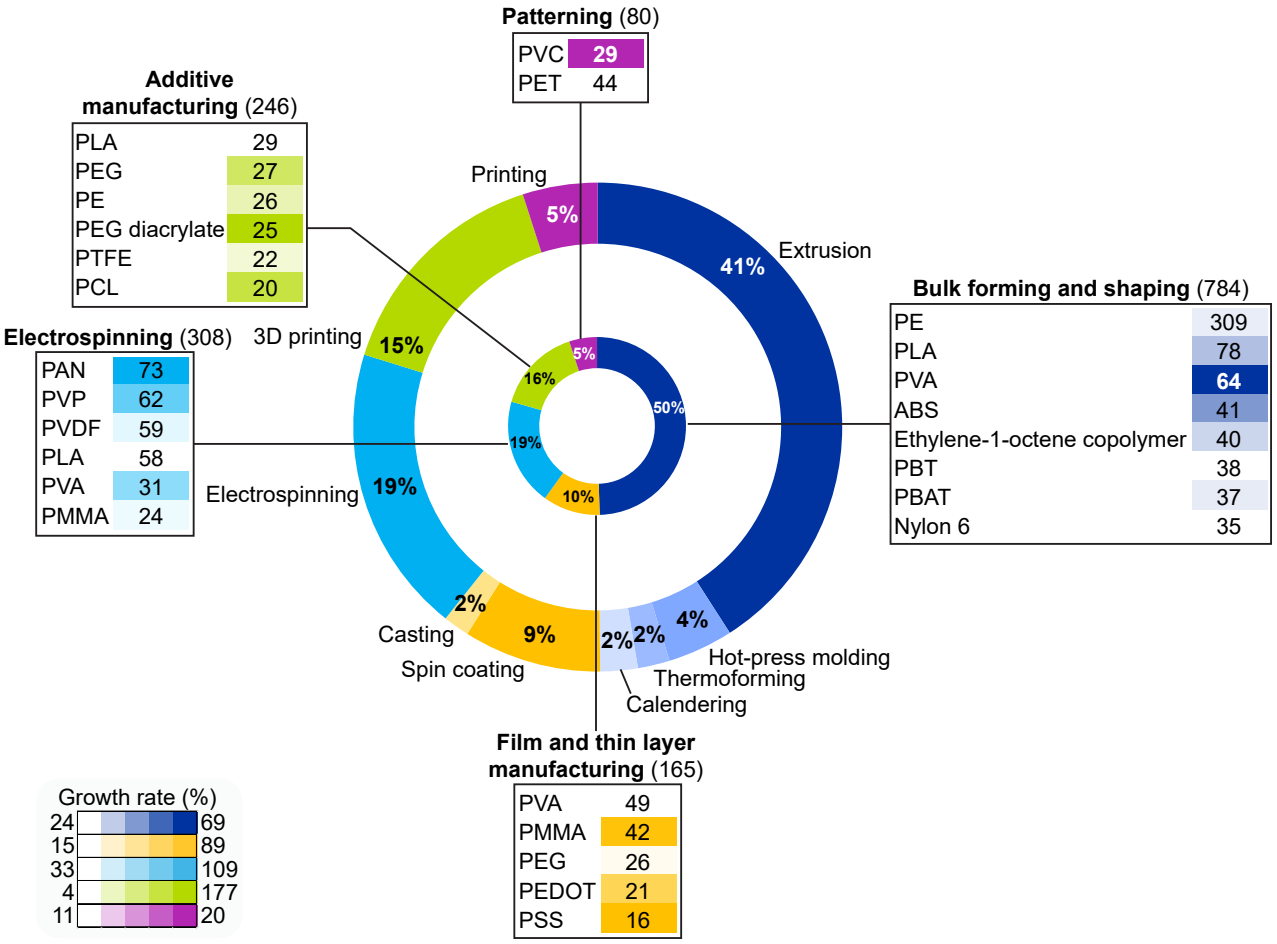


Figure 48. Emerging manufacturing processes in the patent families landscape of polymer based flexible electronics. Inner ring represents the major categories of emerging manufacturing processes and the outer ring depicts the corresponding individual processes. Heat map tables are the top emerging polymer substances in respective processes. Data includes patent publications from the CAS Content Collection for the period 2020-2024.

roles—humidity-responsive or ion-conducting films—though water sensitivity and limited thermal stability restrict broader application.[659] Overall, the growth distribution reflects the chemistry required for high quality thin films, materials with predictable solubility, smooth surface energetics, and stable postdeposition morphology are suitable for these processes.

Electrospinning enables polymers to be drawn into micro- to nanoscale fibers with exceptionally high surface area, tunable morphology, and mechanical flexibility, making them ideal for stretchable and conformal electronic architectures. By producing ultrathin, porous, and lightweight fiber networks, electrospun structures improve breathability, strain accommodation, and sensor responsiveness, supporting their integration into next-generation flexible and wearable electronic devices.[660] Polymers in this space exhibit a growth rate of (33–109%). PAN (~109%) performs exceptionally well due to its nitrile-rich backbone, which supports stable jet formation and yields strong, uniform fibers that can be further carbonized for conductive networks.[661, 662] PVP and PVA are electrospin ready because their hydrogen-bonding capability produces smooth, defect-free mats ideal for electrolytes, filtration, and flexible supports.[663] PVDF emerges next, favored for its strong dipoles and ability to form, β-phase rich electroactive fibers that enhance piezoelectric or triboelectric transduction.[664] PMMA and PLA show moderate growth, contributing optical clarity, dielectric stability, or biocompatibility in applications where

nanofiber morphology improves breathability, stretchability, or tissue integration.[665, 666] Overall, electrospinning prefers polymers with predictable solution rheology, chain alignment potential, and end-use functional performance.

Additive manufacturing enables polymers to be digitally patterned into customized, lightweight, and mechanically compliant architectures using layer-by-layer 3D printing approaches. It requires polymers with precise melt rheology, reliable curing kinetics, and strong interlayer bonding to support complex 3D geometries, embedded channels, and flexible structural components. Across this category, patents focus on modifying the polymers to make them compatible with the above-mentioned processes.[667] PTFE leads this category (~177%), as its C–F backbone provides high thermal stability and low-friction melt flow for printing robust insulating parts via modified fused filament formation (FFF) routes. PE-based materials follow, benefiting from clean melt flow and strong interlayer fusion ideal for flexible housings and low dielectric supports. PEG diacrylate and PCL occupy the next tier, each matching the viscosity and crosslinking demands of stereolithography (SLA) and digital light processing (DLP), where PEG diacrylate forms uniform photocured networks for soft, bio-integrated components while PCL offers low temperature printability and mechanical compliance for flexible frameworks.[668, 669] PVA and PEG function primarily as soluble supports, humidity responsive matrices, or sacrificial layers, with their hydrophilicity limiting long term structural use. Recent developments include, light/heat-curable hybrid systems incorporating phase-change materials,[670] photocurable polyurethane-acrylate elastomers formulated as one-component printable liquids, and elastomer–shape-memory composites fabricated through either molding or 3D printing among others.[671, 672]

Patterning techniques such as printing, define microscale conductive, dielectric, or sensor architectures in polymer films, enabling precise spatial control without compromising mechanical compliance. Patterning techniques prioritize polymers that maintain dimensional stability, support fine-feature definition, and exhibit strong compatibility with inks, coatings and beam-based processes. PVC exhibit higher growth rate compared to PET in this space. PVC supports patterned electronic labels, laminated structures, and thermoformed printed components. Recent patents demonstrate PVC's compatibility with UV-ink patterning, room temperature embossing, and solvent-based processing, enabling efficient fabrication of decorative and functional multilayer surfaces.[673, 674] Its solubility and thermoformability further support applications requiring conformal geometries without major workflow modifications. PET is emerging due to its optical clarity, thermal stability, and smooth surface, enabling UV/E-beam patterning, conductive printing, and multilayer optical structures without deformation, including metallization–demetallization cycles.[675-677]These inventions demonstrate PET's ability to accommodate fine feature printing, and integration with display or light management layers, making it a preferred choice in flexible electronics and security packaging.

Overall, the patent landscape shows the emergence of an integrated manufacturing ecosystem. Bulk forming supplies scalable structural substrates; coating and electrospinning expand material functionality through engineered dielectrics and nanostructures; additive manufacturing introduces programmable geometries and embedded function; and PET/PVC patterning delivers high resolution features for sensing, security, and display technologies. Together, these advances demonstrate how flexible polymer electronics are increasingly produced through coordinated, multistep workflows that support both large-scale manufacturing and highly customized device designs.

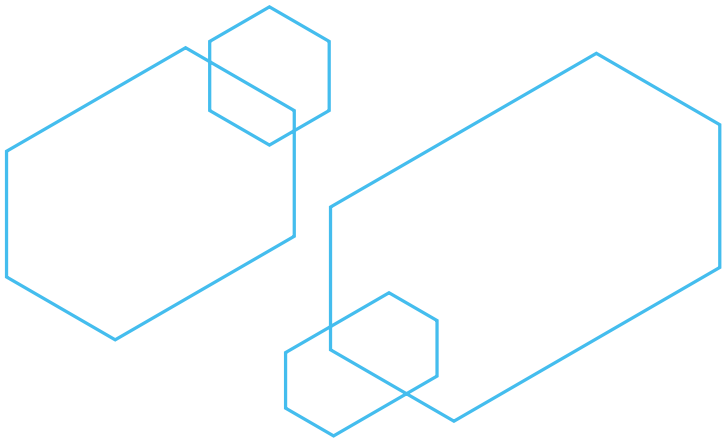
6.5 Summary and Outlook

From 2015–2024, polymer-based flexible electronics has progressed from research driven field to a commercially advancing technology domain shaped by strong regional concentration, maturing material platforms, and increasingly integrated manufacturing

ecosystems. Materials innovation is shifting toward multifunctional polymer systems capable of meeting mechanical, electronic, and interfacial requirements simultaneously. Fluoropolymers, polysiloxanes, conductive polymers, and hydrogels exemplify this trend by performing reliably across multiple application categories, reducing the need for separate material sets. A divergence persists between academia's emphasis on sustainable, bioderived polymers and industry's reliance on robust high-performance chemistries, highlighting ongoing challenges in commercializing greener alternatives.

Application patterns reveal that emerging sectors such as wearables, flexible electrical circuits and e-skin demand broader material portfolios due to their complex mechanical and physiological constraints, while mature areas like OLED and EL displays rely on established, optimized polymers. Manufacturing advances further reinforce this shift: bulk forming provides scalable structural substrates; solution processing and electrospinning enable functional nanostructured layers; additive manufacturing introduces programmable geometries; and precision patterning enables high resolution device integration.

Overall, the trajectory of flexible electronics is increasingly defined by chemistry-driven, multifunctional material platforms and co-optimized processing pathways, rather than isolated material breakthroughs. Future competitive advantage will stem from mastering material process integration across rigid–flexible–stretchable regimes, enabling the next-generation of adaptive, scalable, and high performance flexible electronic systems.



7. Advances in Polymer Membranes

The NLP analysis revealed polymer membranes are an emerging area of scientific interest. Polymer membranes are thin, engineered films made from polymer materials that act as selective barriers, allowing specific molecules or ions to pass while blocking others, and they are widely used across industries for separation, purification, and controlled transport processes.[678] Depending on their structure—porous or dense—they can remove particles and microbes from water, desalinate seawater, separate gases like CO_2 or hydrogen, enable solvent purification in chemical processing, and serve as ion-conductive layers in batteries, fuel cells, and electrolyzers.[679] Moreover, their selectivity can be fine-tuned through chemical modification, crosslinking, or blending with other materials to achieve specific separation requirements.[680]

The increasing use of polymer membranes is driven by the need for more energy-efficient, modular, and lower-cost alternatives to traditional thermal or chemical separation methods, as well as by advances in polymer chemistry that have improved selectivity, durability, and fouling resistance. As a result, polymer membranes have become essential technologies in water treatment, clean energy systems, industrial gas processing, biotechnology, and food production. This section highlights how polymer chemistry enables the development of diverse polymer membranes and supports their broad range of applications in academic literature and patent families for the period 2015-2025.

7.1 Research Literature Analysis

7.1.1. Publication Trends in Academic Journals and Patent Literature

To define the scope of the polymer membrane landscape, we extracted journal articles and patent families associated with polymer membranes from our polymer dataset for the period 2015–2025. We analyzed the publication trends for these documents as shown in **Figure 49**. The publication trends show that polymer membranes constitute a mature, commercially driven field with strong industrial engagement. The predominance of patents (57%) reflects sustained investment

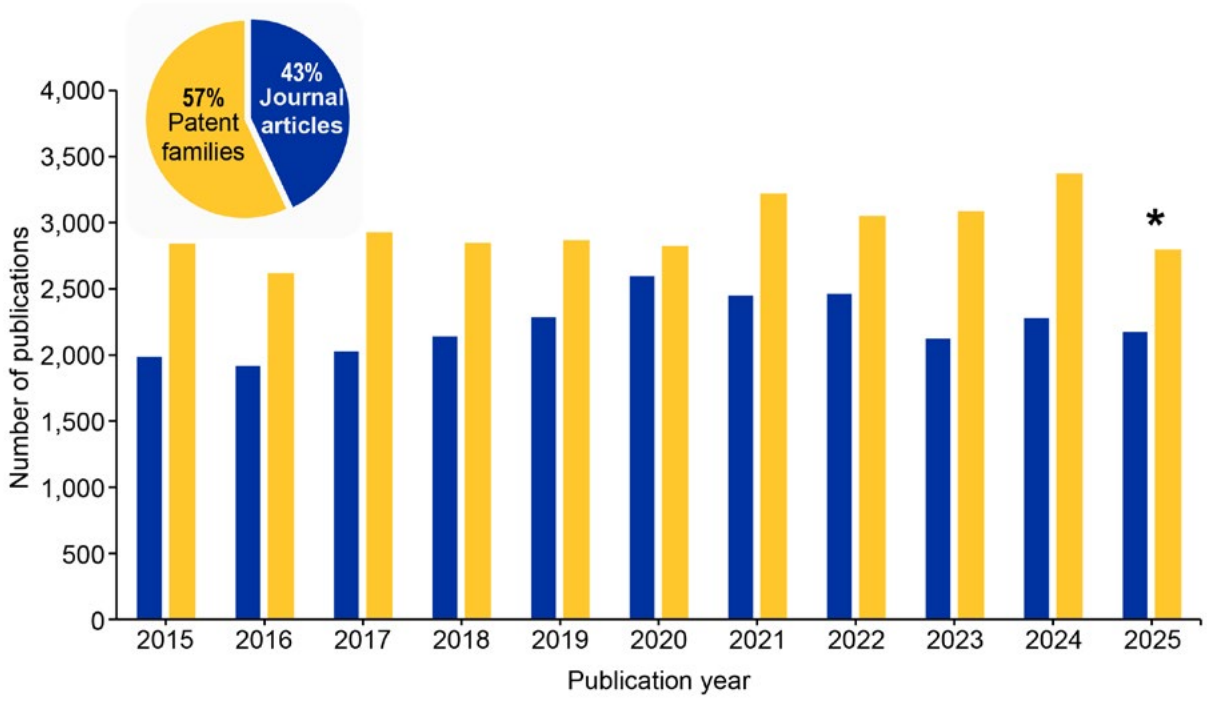


Figure 49. Trends for polymer membranes related publications in the polymer dataset for the period 2015-2025 from the CAS Content Collection. *Data only for the months January to November in 2025.

in intellectual property protection, while the steady publication levels across journals and patents indicate a shift from rapid discovery toward incremental optimization and application-focused development. This stability aligns with technological maturity, where competitive advantage is achieved through process and performance improvements rather than breakthrough innovations.

7.1.2.Corporate and Academic Patent Ownership

We then analyzed the geographical distribution of patents to distinguish commercial and academic contributions. **Figure 50** summarizes the global commercial landscape in research and development on polymer membranes. The patent activity for polymer membranes reveals a highly concentrated innovation ecosystem dominated by Asian enterprises, with China commanding the majority share of patent families, followed by Japan and South Korea. However, Japanese firm, Toray Industries stands out as the undisputed leader, demonstrating exceptional R&D commitment and technical depth in membrane technology. Other Japanese firms like Fujifilm Holdings, Asahi Kasei, and Nitto Denko are also contributing significantly, highlighting Japan's established leadership in high-performance polymer materials and specialty membranes. Chinese petrochemical giants Sinopec and CNPC represent the second tier of innovation activity, reflecting state-driven priorities in separation and filtration technologies. South Korean and U.S. companies occupy mid-tier positions, represented by contributors such as LG Chem and 3M, indicating targeted but less extensive investment relative to East Asian leaders. European companies, including BASF and a few specialized firms such as Sika and Syensqo, show a narrower but technologically focused engagement, reflecting Europe's emphasis on advanced materials for regulated, sustainability-driven markets.

The organizational diversity spanning petrochemical companies, chemical manufacturers, and industrial conglomerates indicates that polymer membrane technology sits at the intersection of multiple industrial value chains. The presence of both specialized chemical firms and diversified conglomerates suggests different innovation strategies—

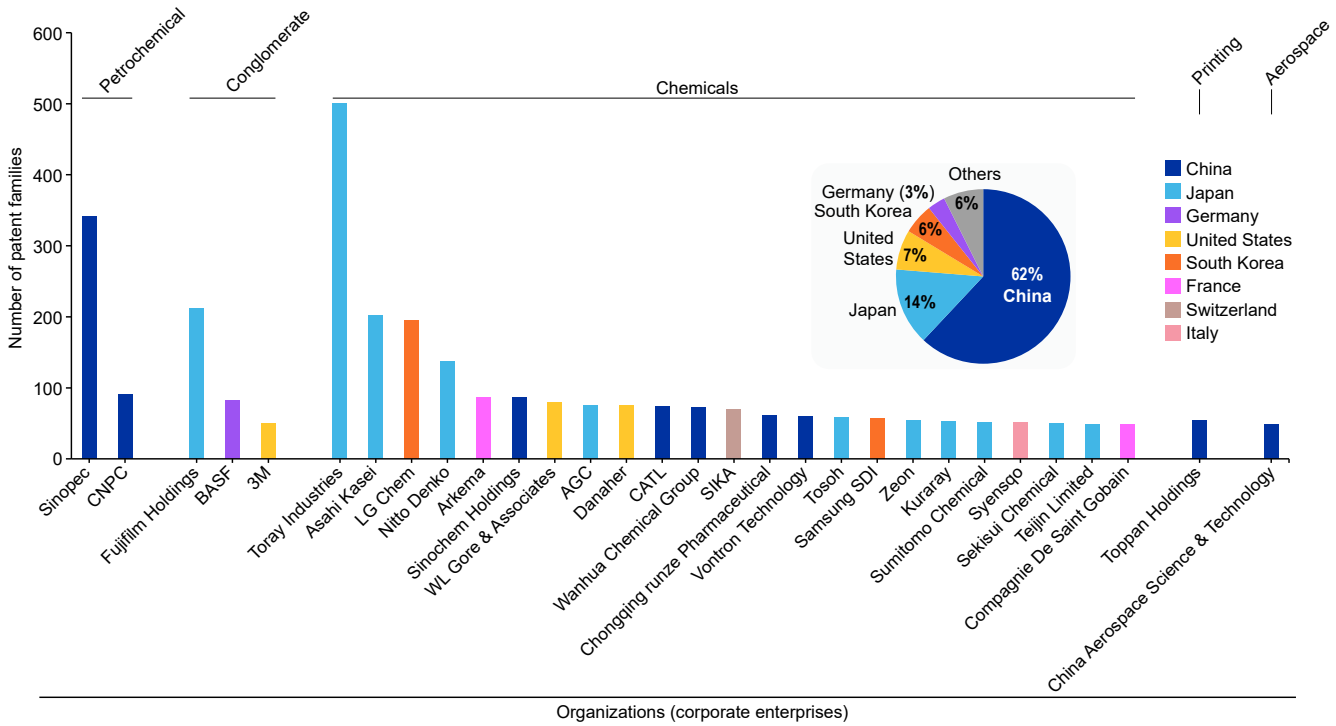


Figure 50. Leading organizations (corporate enterprises) categorized by industry type and geographical distribution for patent publications related to membranes in the polymers dataset for the period 2015-2025 from the CAS Content Collection.

specialist players focusing on core membrane chemistry versus integrated companies developing application-specific solutions. The relatively modest representation of Western entities, particularly European and American firms, highlights a competitive disadvantage or strategic deprioritization in this technology domain. This geographic and organizational concentration has significant implications for global supply chain dependencies, technology access, and competitive dynamics in membrane-critical applications such as water treatment, gas separation, and battery technologies.

To identify the research and academic institutions driving innovation in this field, **Figure 51** maps their geographical distribution and highlights the top 30 institutions based on patenting activity. Analysis of the institutional landscape shows a strong dominance of Chinese organizations, with only a single non-Chinese institution—South Korea's Korea Research Institute of Chemical Technology (KRICT)—appearing in the dataset. Notably, Tiangong University (TU; formerly Tianjin Polytechnic University) ranks first in patent output, followed by the Chinese Academy of Sciences. To contextualize this outcome, it is important to consider the historical and structural background of these institutions.

Chinese Academy of Sciences comprises a broad network of high-ranking research institutes that, while not exclusively specialized in polymer membranes, collectively contribute substantial research activity in this domain. TU, in contrast, has a long-standing, focused specialization in membrane science. It established China's first dedicated membrane research unit in 1974—the Membrane Separation Technology Research Laboratory[681]—and has since expanded its capabilities through the creation of municipal, state, and national laboratories. Key milestones include the 2015 establishment of the State Key Laboratory of Separation Membranes and Membrane Processes and, most recently, the opening of the National Key Laboratory of Advanced Separation Membrane Materials in 2025.[682]

TU's research leadership spans a wide array of advanced membrane technologies. Examples include innovations in wastewater treatment using PVDF ultrafiltration membranes,[683] PDA-based nanofiltration membranes,[684] polyimide

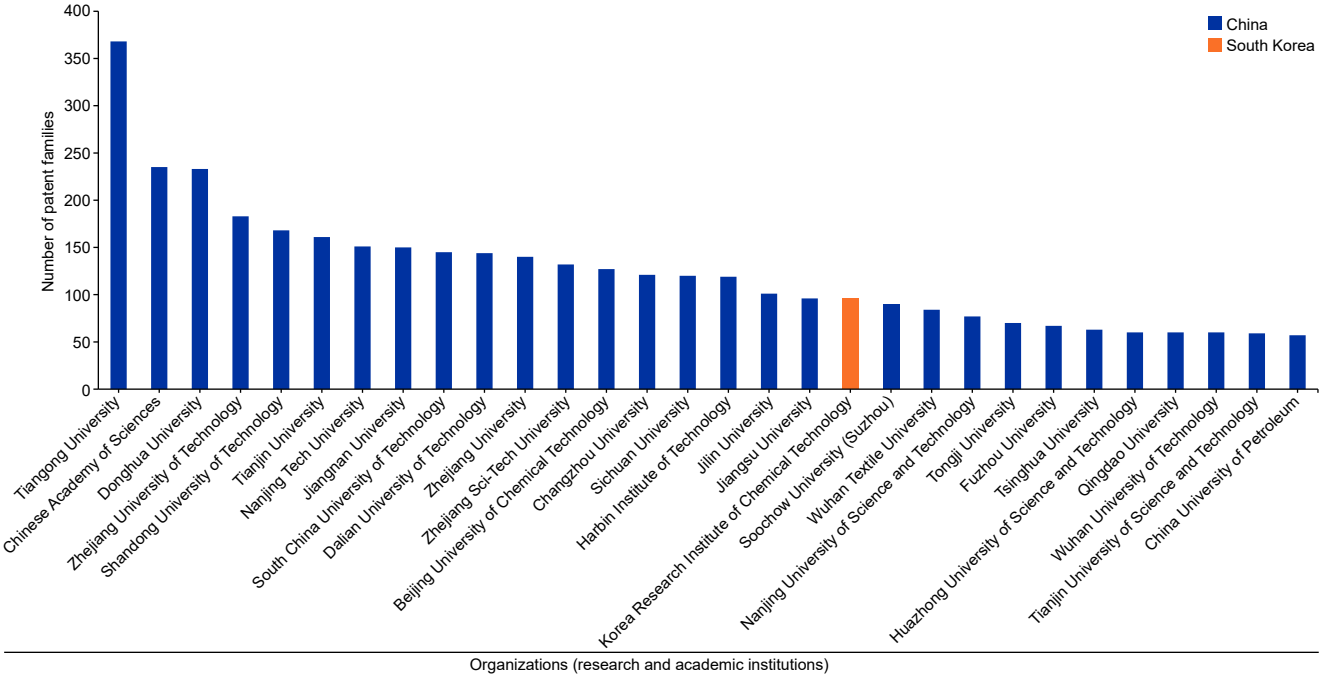


Figure 51. Leading organizations (research and academic institution) with their country of origin for patent publications related to membranes in the polymers dataset for the period 2015-2025 from the CAS Content Collection.

membranes for CO_2-selective gas separation,[685] polyamide membranes for LIB separators,[686] and pH-responsive polyethersulfone (PESU) membrane systems.[687]

KRICT serves as South Korea's counterpart to TU, though with the distinction of being a research-focused institute rather than a traditional teaching university. Operating at the national level, KRICT conducts research across several strategic areas, including chemical processes and advanced energy materials, and houses dedicated centers for separations,[688] polymer science,[689] and battery technologies,[690] among others.

7.2 Emerging Trends of Leading Topics in Polymer Membranes

7.2.1. Analysis of the Top Topics in Polymer Membranes

To further evaluate commercialization trends in this field and to understand how polymer membranes are being applied in practice, we conducted a detailed analysis of the CAS-indexed scientific concepts associated with polymer-membrane-related patents from 2015 to 2025 (**Figure 52**). These concepts were then classified into six categories based on their nature: structural, polymer class, application, method, property, and process (**Figure 52A**). In addition, we assessed the growth rates of these concepts between 2020 and 2024 to identify emerging areas and fields exhibiting notable momentum over the past five years (**Figure 52B**).

The distribution of top 30 concepts in polymer membrane research reveals a field dominated by established polymer classes, with fluoropolymers commanding the largest patent portfolio, followed by polyesters and polyoxyalkylenes. This hierarchy reflects the historical importance of high-performance polymers in demanding separation applications requiring chemical resistance, thermal stability, and mechanical durability. The strong representation of structural concepts such as plastic films and nonwoven fabrics indicates substantial emphasis on physical architecture and morphology control as critical performance determinants. Applications span diverse industrial sectors, with coating materials, crosslinking agents, and adhesives featuring prominently, suggesting that membrane technology extends beyond standalone filtration into composite material systems and multifunctional platforms.[691] The relatively balanced distribution across polymer classes, structural features, and processing methods demonstrates the multidisciplinary nature of membrane innovation, requiring simultaneous optimization of material chemistry, nanoscale architecture, and manufacturing approaches.

The growth rate analysis reveals a dramatic shift in research priorities, with secondary battery separators exhibiting exceptional expansion, reflecting the global electrification transition and energy storage demands. This explosive growth contrasts sharply with declining interest in traditional concepts like fluoropolymers, polyurethanes, and plastic films, suggesting market saturation or technological maturity in conventional membrane applications. Electrospinning shows robust growth as an enabling fabrication method, aligning with increased focus on nanostructured membranes and high-surface-area architectures. The simultaneous decline in nonwoven fabrics and extrusion processes indicates a shift from traditional manufacturing toward advanced processing techniques offering superior control over membrane microstructure. Notably, crosslinking agents, antioxidants, and coupling agents demonstrate positive growth, suggesting that performance enhancement through chemical modification and interfacial engineering represents a key innovation pathway. The divergent trajectories between established polymer classes and emerging applications underscore a field transitioning from material-centric to application-driven innovation, where membrane development increasingly responds to specific technological challenges in energy storage, environmental remediation, and advanced manufacturing.

7.2.2. Publishing Trends of Application-based Topics

To better understand how patents are distributed across different end-use areas in polymer membrane field, we further assessed the

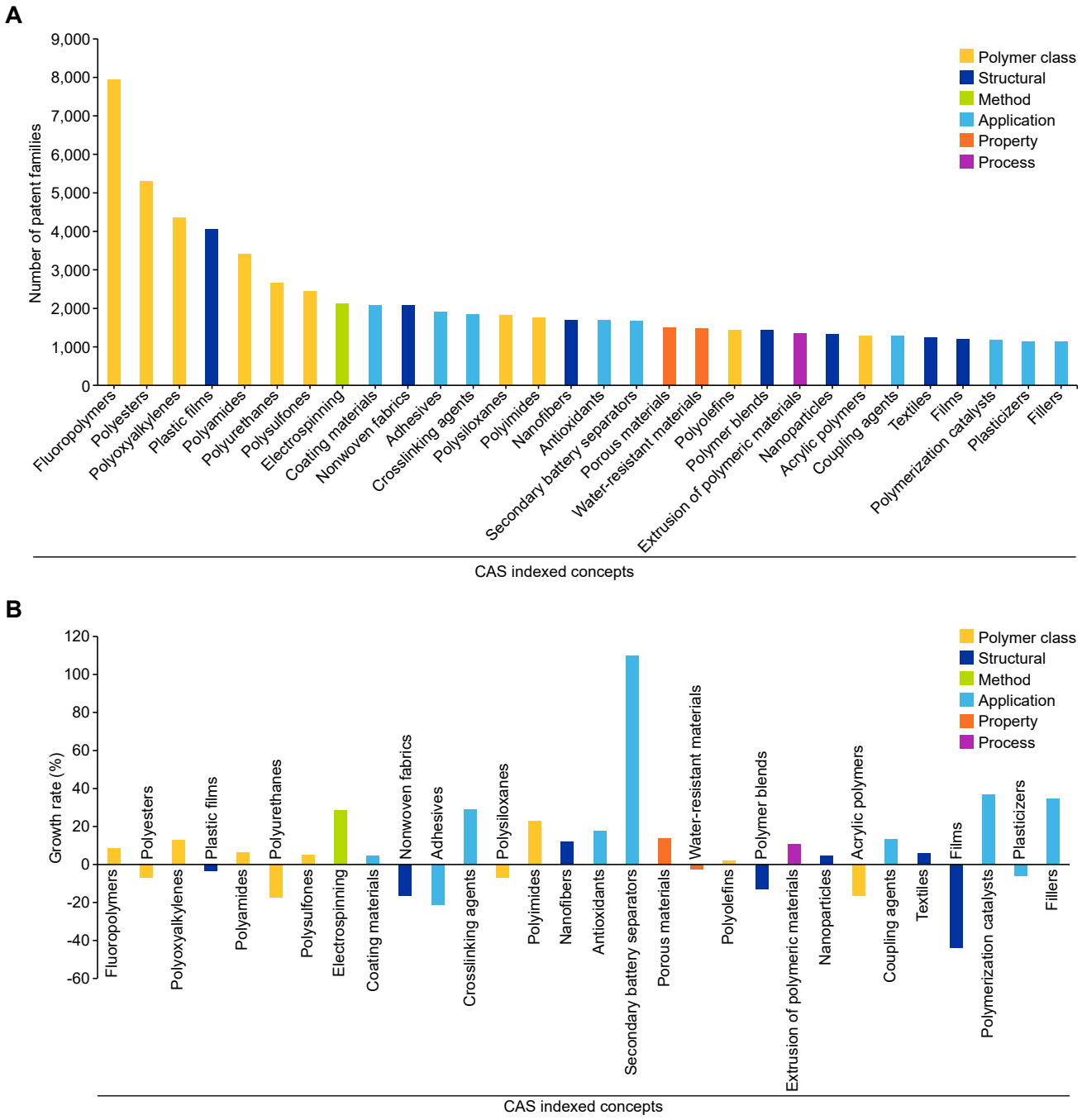


Figure 52. Leading CAS-indexed concepts by (**A**) count of patent publications and (**B**) relative growth rates for the period 2020-2024. These concepts are grouped into categories including structural, polymer class, application, method, property and process. Data includes patent publications for the period 2015-2025 from the CAS Content Collection.

publishing trends of application-based topics or CAS-indexed concepts spanning 2015–2025 in this domain (**Figure 53**). The publication trends reveal a dramatic transformation in polymer membrane research, with secondary battery separators experiencing substantial growth to become the dominant application category, particularly after 2020. This surge reflects the global electrification transition driven by electric vehicles, renewable energy storage, and portable electronics. Polymer membranes serve as critical safety components in batteries by providing ionic conductivity while preventing electrode short circuits.[692, 693] Growth accelerates due to stringent safety requirements, demands for higher energy density, faster charging, and diversification of

battery chemistries including solid-state and lithium-sulfur systems requiring continuous innovation in ionic selectivity, mechanical properties, and electrochemical stability.[694]

Crosslinking agents demonstrate sustained upward growth, indicating that membrane performance increasingly depends on chemical modification and stabilization strategies. Crosslinking enables dimensional stability, solvent resistance, and mechanical robustness in membranes, essential for harsh environments like organic solvent nanofiltration and high-temperature fuel cells.[695] Antioxidants exhibit steady growth, reflecting industry focus on membrane durability in oxidative environments and the transition toward commercial deployment where operational lifetime determines cost-effectiveness.[696] Fillers also show overall growth, reflecting continued interest in mixed-matrix membranes where inorganic particles enhance mechanical strength, thermal stability, and separation performance by combining polymer processability with functional additives like nanoparticles or zeolites.[697]

Coupling agents exhibit moderate growth, facilitating interfacial compatibility between organic polymer matrices and inorganic fillers to optimize composite membrane performance.[698] Coating materials show strong growth through 2022 before declining, suggesting potential market saturation or technological maturation in surface modification approaches.[699] Polymerization catalysts show notable expansion, reflecting increased focus on controlled polymer synthesis that enables researchers to create membrane materials with precise molecular architectures, uniform structures, and tailored properties rather than relying on trial-and-error approaches.[700]

The convergence of multiple application categories at elevated levels after 2020 reflects systemic drivers beyond individual application needs. The sustainability imperative and energy transition create demand for advanced membrane technologies in batteries, efficient chemical separations, and durable material systems. Manufacturing maturation enables commercial-scale production of sophisticated membrane architectures previously confined

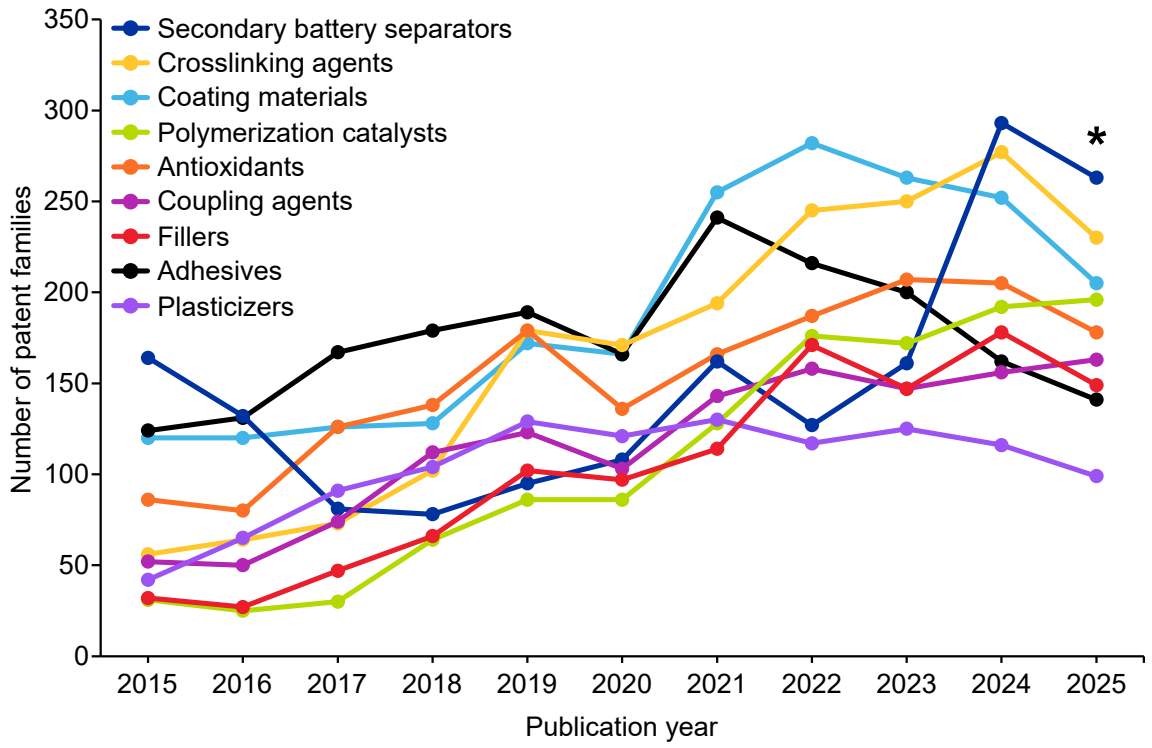


Figure 53. Publication trends of patent families for the application-related CAS-indexed concepts for the period 2015-2025 from the CAS Content Collection. *Data only for the months January to November in 2025.

to laboratory demonstrations, reducing the gap between research innovation and industrial implementation. The relative decline in plasticizers and recent plateauing or decline in several mature categories including coating materials and adhesives indicates commoditization, while research investment concentrates in high-value areas like energy storage and chemical stabilization where substantial performance gaps and compelling commercial opportunities remain.

To determine which polymers are driving these applications, we identified the key materials involved and highlighted those showing the most rapid growth in patent activity (**Figure 54**). Our analysis reveals coating materials and crosslinking agents as the most researched application categories in absolute terms, though secondary battery separators represent the fastest-growing segment with distinct polymer requirements.

In battery separator applications, PE dominates the patent landscape but shows modest growth, reflecting its established position as the industry standard separator material valued for thermal shutdown capability, chemical stability, and mechanical strength that prevents electrode contact while allowing ionic transport.[701] PVDF exhibits substantially higher growth, indicating intensifying research into this high-performance polymer for advanced battery chemistries requiring superior electrochemical stability windows, thermal resilience, and electrolyte compatibility essential for high-voltage and next-generation solid-state systems.[702, 703] The strong growth in specialty polymers like CMC-Na, HFP-VDF copolymers, and PEG reflects diversification beyond commodity separators toward functionalized materials offering enhanced safety features, improved wettability, and compatibility with emerging electrolyte formulations.[704]

Coating materials segment represents the largest research area, reflecting the critical importance of surface treatments. Polyolefins such as PE and PP appear as major volume contributors due to their mechanical robustness, hydrophobicity, and chemical inertness, which make them suitable as protective or structural coating layers.[705, 706]

In contrast, PVDF and PTFE represent the most dynamic growth segment. PVDF is widely used as a chemically resistant, weatherable, and thermally stable membrane material, particularly in separation processes and solvent-exposed environments.[707, 708] PTFE, with its ultra-low surface energy and thermal/chemical resilience, supports anti-fouling, non-stick, and low-friction coatings.[709]

In crosslinking agents, PTFE shows the fastest growth despite its smaller patent base, largely due to its use as a chemically inert, thermally stable, and highly hydrophobic membrane material in harsh-environment applications, where its exceptional chemical resistance and durability are essential.[710] PVA leads in patent count due to its high crosslinkability and ability to form stable hydrophilic networks via thermal, or chemical, crosslinking, making it central to pervaporation and proton-exchange membranes. PEG functions as both a crosslinker and pore-former, improving hydrophilicity and antifouling through its hygroscopic and steric-repulsion behavior.[711]

Antioxidants show strong patent activity aimed at preventing oxidative degradation in membranes. PE and PP lead in patent volume because their hydrophobic matrices easily incorporate lipophilic antioxidants such as hindered phenols and phosphites, though dispersion can be limited by low polarity.[712] The highest growth is seen in SBS, reflecting its ability to uniformly disperse phenolic antioxidants within its elastomeric matrix for enhanced oxidative protection.[713]

The coupling agent application reveals PE dominating by patent volume despite lowest growth, reflecting its established role in polyolefin-based composites.[714] High-growth polymers including PVA, PLA, and cellulose reveal shifting priorities toward intrinsically functional materials. PVA demonstrates particularly intense growth, functioning simultaneously as membrane material and coupling agent through abundant hydroxyl groups forming interfacial bonds.[715] Bio-based PLA and cellulose show notably high growth driven by sustainability imperatives.
In polymerization catalysts, PVDF and PP,

reflecting intensive research into controlled polymerization for commercially critical membranes.[716] High-growth specialty polymers including polyethylenimine (PEI), and PEG diacrylate, reveal emphasis on precision architectures. PEI demonstrates intense growth through catalytic synthesis of hyperbranched structures with high amine density for CO_2-selective gas separation.[717] PEG diacrylate enables photopolymerization for spatially controlled fabrication creating gradient structures and microfluidic devices.[718]

In filler applications, SBR, PVA, and PTFE show high-growth, revealing strategic shifts toward specialized matrices. SBR demonstrates highest growth intensity as elastomeric matrices accommodate rigid fillers without cracking, maintain flexibility during thermal cycling, and enable self-healing through chain mobility—critical for mechanically resilient gas separation and battery separators.[719, 720] PVA shows equally intense growth as hydrophilic matrix where water-compatible fillers enhance flux and anti-fouling, while hydroxyl groups improve filler dispersion.[721]

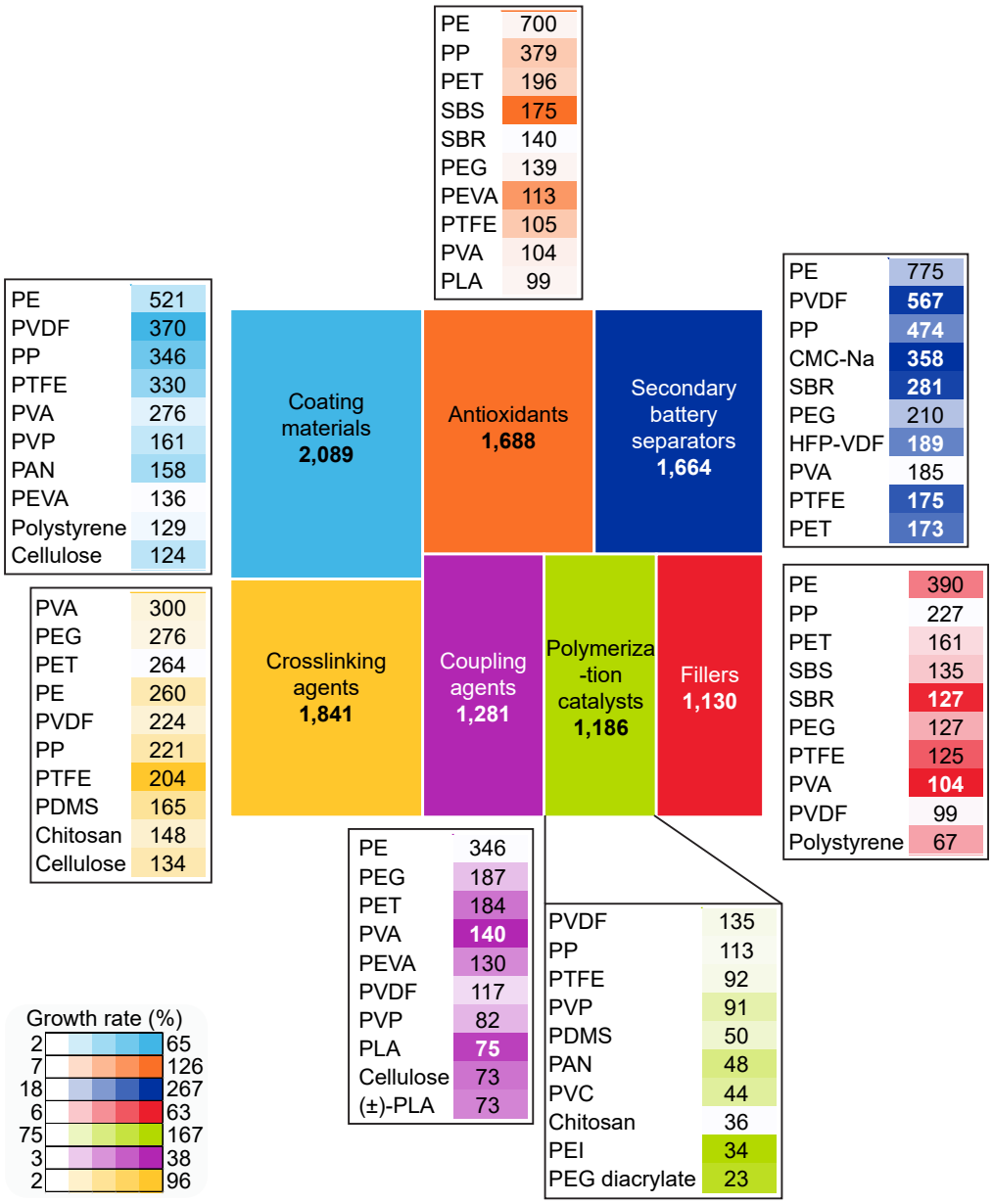


Figure 54. Distribution of patent families across various applications-based CAS-indexed concepts for the polymer membranes in the polymers dataset shown as a treemap. The corresponding heatmap tables highlight the emerging polymers within each application class, ranked by their volume of patents, with color intensity indicating relative growth rates for the period 2020-2024. Data includes patent families in the field of polymers for the period 2015-2025 from the CAS Content Collection.

The polymer-application landscape reveals commodity polyolefins (PE, PP) dominating patent volumes with modest growth indicating maturity, while specialty polymers demonstrate intense growth driven by functionality and sustainability demands. Secondary battery separators exhibit the most dramatic expansion, transitioning from PE's thermal shutdown to PVDF's high-performance electrochemical stability and functionalized copolymers for next-generation energy storage. Fluoropolymers (PVDF, PTFE) show consistent high growth across applications due to chemical resistance and thermal stability, while elastomers (SBR, SBS) and PVA demonstrate exceptional growth through mechanical resilience, self-healing, and intrinsic multifunctionality. Bio-based polymers (PLA, cellulose, chitosan) show elevated growth reflecting sustainability imperatives. The field differentiates between mature commodity applications with incremental optimization and high-value emerging domains (energy storage, CO_2 capture) where innovation concentrates on precision catalytic control, intrinsic interfacial compatibility, and application-specific performance rather than generic material substitution.

To identify the key developers in this application landscape, both the corporate and academic patent assignees were analyzed. **Figure 55** presents the top ten assignees for the top four emerging application-specific topics: A) coating materials, B) crosslinking agents, C) antioxidants, and D) secondary battery separators. Coating materials show the largest number of patents activity, led by Toray Industries, followed by Fujifilm Holdings and then Asahi Kasei; except for Tiangong University, the assignees in this category are predominantly corporate. In contrast, for crosslinking agents, Sinopec leads with 29 patents, and academic institutions constitute the majority (7 out of 10), although each holds comparatively fewer patents (10–18). The antioxidants and secondary battery separator topics exhibit a balanced mix of corporate and institutional participation, with Sinopec and Toray Industries remaining key contributors. Across all four topics, assignees are heavily concentrated in China, followed by Japan and South Korea.

7.3 Publishing Trends of Membrane-Specific Topics

7.3.1.Top 30 Membrane-specific Topics

Digging deeper into the patents, membrane-specific topics based on CAS indexed concepts are analyzed, and their document counts across the 2015-2025 period are presented in **Figure 56**. These topics are further grouped into four general categories: properties, structural, filtration and separation.

The top five topics are ultrafiltration membranes, microporous membranes, hollow-fiber membranes, composite membranes and nanofiltration membranes. Ultrafiltration membranes retain macromolecucles and colloids in the ~10-100 nm size range, allowing small solutes to permeate.[722] Whereas nanofiltration membranes lets molecules smaller than about ~1-10 nm to permeate.[723] Microporous membranes are a broader type that typically retain larger particles at the micron level (~1-10 μm) and have an intrinsically larger surface area due to their larger pore size.[724] Hollow-fiber[725] and composite membranes[726] are structural types: hollow-fiber membranes consist of densely packed, hollow tubes that maximize the surface area, while composite membranes incorporate multiple layers of additive-modified materials to enhance mechanical robustness or separation performance. The next five topics are all separation-focused technologies, followed by the remaining topics around ~300 patents and decreasing.

To help determine the emerging membrane-related technologies, the trends of all the topics in **Figure 56** were studied across the period 2015 and 2025 and illustrated in **Figure 57**.

Within the property category (**Figure 57A**), microporous membranes stand out as not only the most dominant by publication volume but also the only one growing over time. This upward trend reflects increasing interest in pore structure, surface area and porosity-driven performance, rather than their conventional role in micro-scale particle retention. Microporous membranes, particularly polyolefin-based types, are widely used as battery separators, where high surface area, controlled pore size and thermal

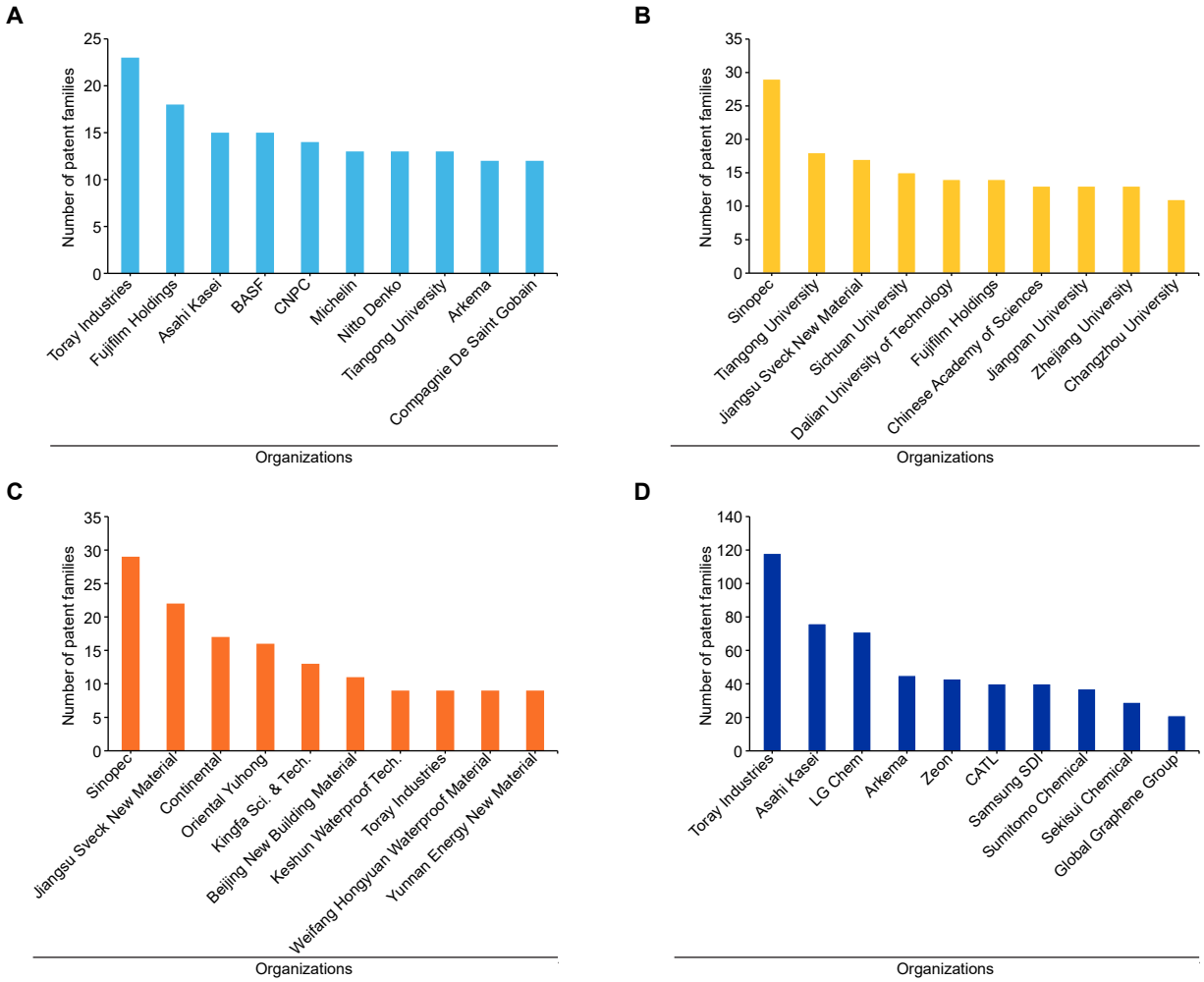


Figure 55. Leading organizations (corporate enterprises and academic institutions) involved in polymer membrane related applications across (**A**) coating materials, (**B**) crosslinking agents, (**C**) antioxidants, and (**D**) secondary battery separators. Data includes patent publications for the period 2015-2025 from the CAS Content Collection.

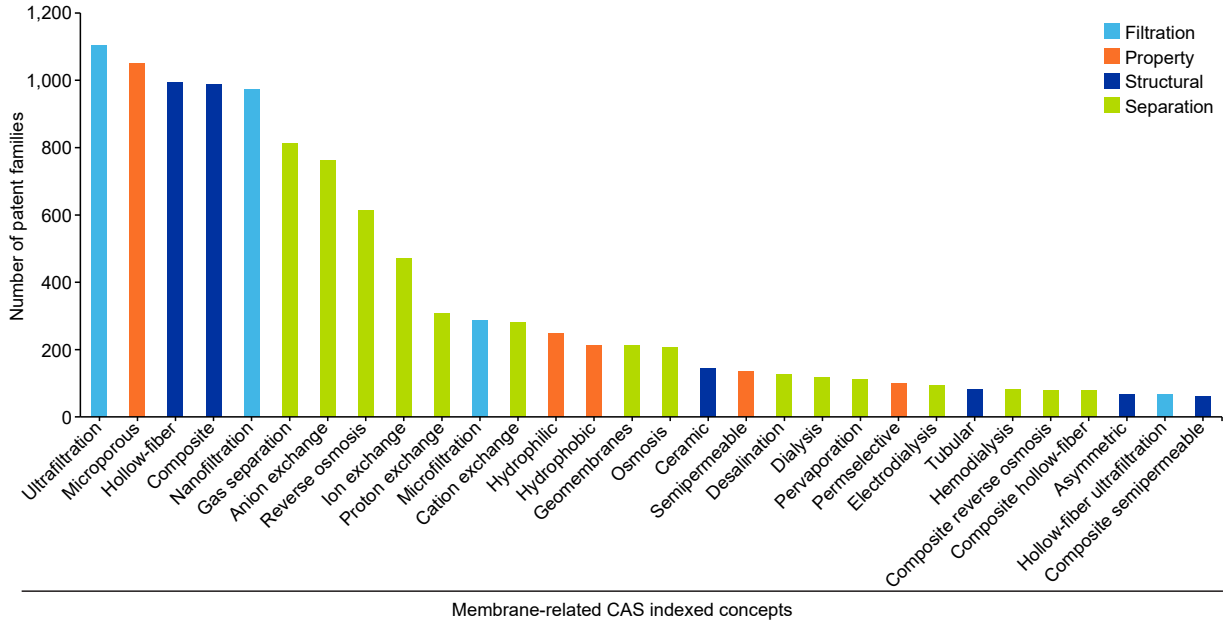


Figure 56. Leading membrane-specific CAS indexed concepts, grouped into four categories of property, structural, filtration and separation. Data includes patent publications for the period 2015-2025 from the CAS Content Collection.

stability are critical.[727] By contrast, hydrophobic, hydrophilic and permselective membranes are more strongly associated with textiles and apparel, and protective materials industries, which exhibit relatively lower growth compared to energy-storage sector.

In the filtration category (**Figure 57B**), nanofiltration membranes showing a positive trend, suggesting increasing industry interest in membrane technologies that molecular-scale separations rather than the upper-nanometer level typical of ultrafiltration membranes. This aligns with global drivers for high-purity drinking water, industrial wastewater treatment, and resource recovery, which favor membranes capable of removing dissolved organics, multivalent ions, and trace contaminants.[728]

Within the structural category, composite membrane stands out with a dramatic rise while the others remain flat or decline over the ten-year period. Composite designs, typically involving multilayer architectures or additive-enhanced selective layers, are increasingly important for achieving tailored mechanical, chemical, or transport properties.[729] Their rising prominence is closely tied to advanced fuel-cell, electrolysis systems and water purification.[730]

Finally, the anion exchange membrane from the separation category shows strong positive growth compared to the others. Anion exchange membranes enable low-cost alkaline operation, allowing fuel cells and electrolyzers to use non-precious metal catalysts while maintaining high ionic-conductivity and durability.[731] Their rising prominence is further driven by rapid advances in anion exchange membrane-based fuel cells, where modern polymer architectures have significantly improved chemical stability and performance. Anion exchange membranes are also central to emerging CO_2 electrolysis technologies, where they facilitate ion transport in high-efficiency, zero-gap reactors for CO_2-to-fuel conversion.[732]

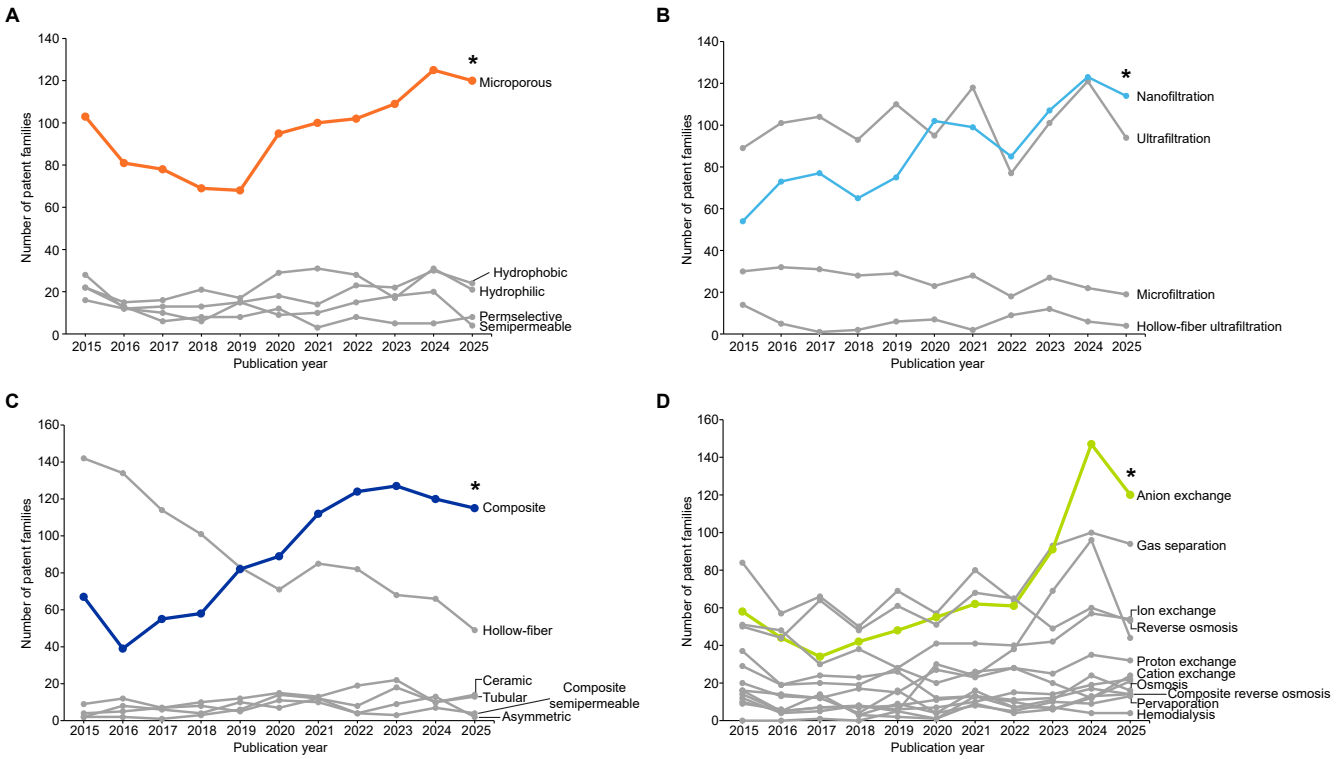


Figure 57. Publication trends of membrane related CAS indexed concepts categorized as (**A**) property based, (**B**) filtration, (**C**) structural, and (**D**) separation membranes, based on patent publications for the period 2015–2025 from the CAS Content Collection. *Data only for the months January to November in 2025.

To further understand the emerging polymers within the above emerging membrane technologies, we analyzed the top polymer substances based on their growth rate (**Figure 58**). The growth rate patterns in microporous membranes reveal distinct trends based on polymer functionality, with structural matrix materials showing steady maturation while functional additives and surface modifiers experience rapid expansion. Specialty functional polymers such as polystyrene and SBR show the highest growth, driven by niche applications requiring tailored mechanical or adhesive performance; SBR in particular grows rapidly due to its roles as both a negative-electrode binder[733] and an adhesive resin in separator coatings.[703] CMC-Na displays moderate growth, functioning mainly as a pore-forming additive, thickener, and binder, with recent work[734] demonstrating its effectiveness in aqueous coating layers for uniform filler dispersion and strong adhesion on polyolefin separators. PVDF and PEG occupy the next tier, with PVDF serving as a widely used structural membrane-forming polymer, while PEG acts as a pore-forming additive enhancing hydrophilicity rather than forming the membrane matrix. Finally, established structural polymers—PE, PTFE, and PVDF—show moderate, mature growth (104–119%) consistent with their long-standing use as robust microporous frameworks undergoing steady incremental optimization.[735]

In the composite membranes category, m–PDA–TMC copolymer is the most emerging. The patents suggest that it is driven by rapid innovations in interfacial polymerization and precision selective-layer engineering. For example, m–PDA–TMC used in forming the active selective layer (separation layer) of polyamide composite membrane[736] with application in including electrical neutrality[737] and temperature-resistant reverse osmosis

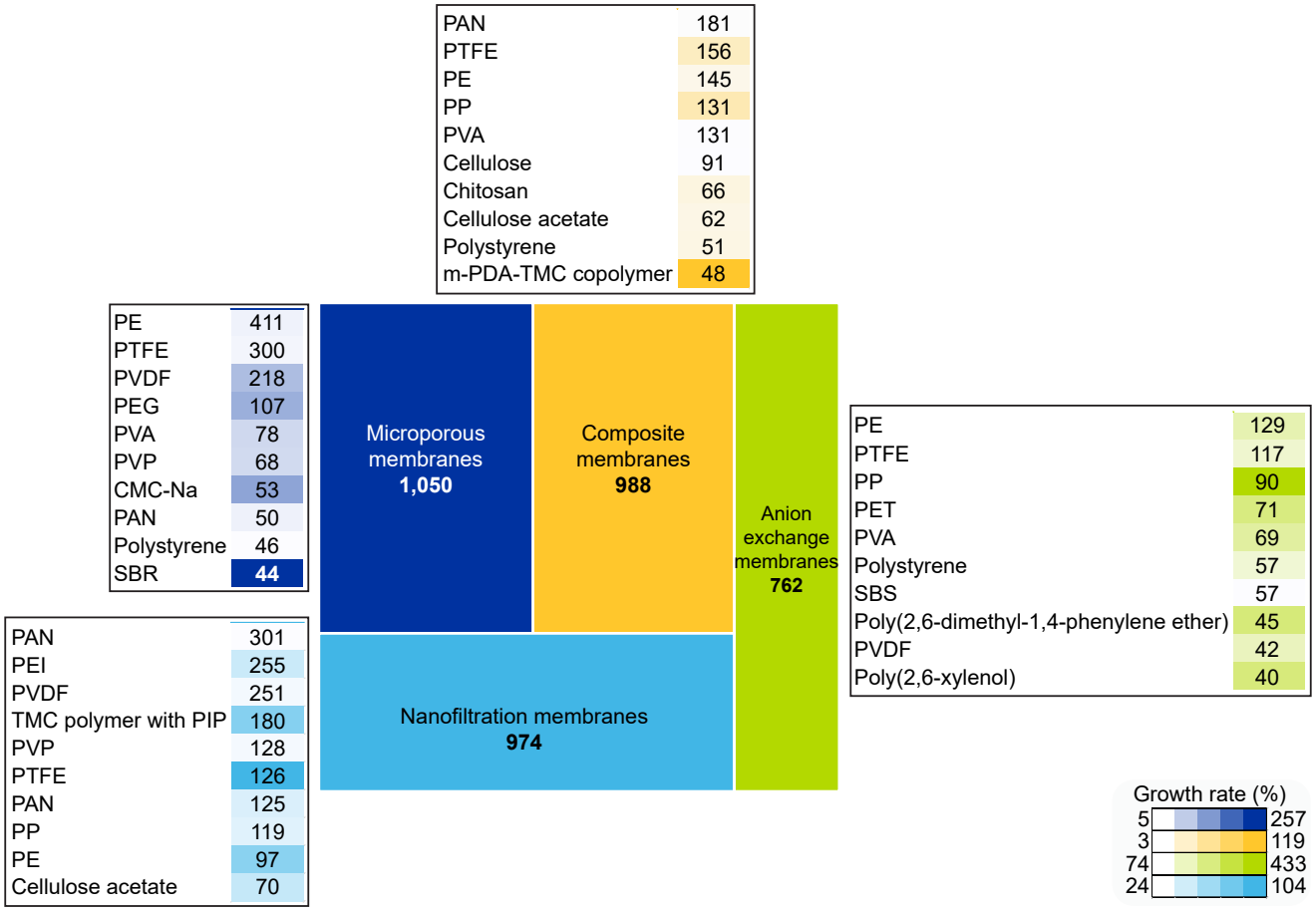


Figure 58. Distribution of patent families across various membrane-based CAS-indexed concepts in the polymers dataset shown as a treemap. The corresponding heatmap tables highlight the emerging polymers within each membrane class, ranked by their volume of patents, with color intensity indicating relative growth rates for the period 2020-2024. Data includes patent families in the field of polymers for the period 2015-2025 from the CAS Content Collection.

systems.[738] Functional modification polymers such as PVA follow, with steady growth owing to their roles in enhancing hydrophilicity, adhesion, and interlayer compatibility in composite membrane structures. Structural support polymers—PAN, PTFE, PE, and PP— continue to exhibit moderate, mature growth, reflecting their established function as robust porous substrates optimized for mechanical strength and interfacial compatibility. Sustainable matrix materials, including cellulose and chitosan, show similar moderate adoption driven by interest in environmentally friendly membrane platforms. Overall, while composite membranes rely on proven substrate materials, the strongest innovation momentum remains concentrated in selective-layer chemistry and advanced interfacial engineering.

For nanofiltration membranes, PTFE shows the highest growth rate. Recent patents discusses the role of PTFE as a chemically robust, mechanically stable porous substrate that, once surface-modified, provides the foundation for forming dense, defect-free polyamide selective layers capable of withstanding strong organic solvents and enabling high-performance nanofiltration, including enhanced lithium recovery.[739, 740] TMC polymer with PIP form the polyamide selective layer through interfacial polymerization, creating the core nanofiltration barrier responsible for molecular-scale separation, charge-based selectivity, and controlled pore sizes (0.5–2 nm).

Among the four categories, polymers in the anion exchange membranes category show the highest growth rate of 74-443%, indicating one of the most dynamic and rapidly evolving membrane technology sectors. This exceptional growth pattern reflects the critical role of anion exchange membranes in emerging energy technologies, particularly fuel cells, electrolyzers, and next-generation battery systems where ionic conductivity and alkaline stability are paramount. PP shows the highest growth rate with innovations in applications that primarily include methods of preparing fuel cells,[741] and for electrodialysis.[742] Poly(2,6-dimethyl-1,4-phenylene ether) shows high-growth rate with a moderate patent volume. It is widely used as a main-chain polymer backbone in anion exchange membranes, as it provides excellent thermal stability, easy functionalization and good chemical resistance and used to build durable, high-conductivity anion exchange membranes for electrosorptive deionization,[743] water-treatment ion-exchange systems,[744] and alkaline fuel-cell applications.[745] The moderate growth in established base polymers (PE, PTFE) indicates continued optimization of proven materials for radiation grafting and chemical functionalization to introduce ionic groups, while the explosive growth in specialty materials signals a technology transition toward purpose-designed polymers rather than modified commodity plastics.

The patent assignees of the four membrane-specific topics were analyzed (**Figure 59**). Leadership in membrane technologies varies sharply by segment, with microporous membranes dominated by major industrial players—especially Toray Industries and Asahi Kasei—reflecting a mature, manufacturing-intensive market with high entry barriers, while composite, nanofiltration, and anion exchange membranes show strong academic leadership, led by institutions such as Tiangong University, Zhejiang University of Technology, Dalian University of Technology, and Fudan University, indicating early-stage, research-driven innovation with significant opportunities for technological advancement and future commercialization; overall, patent activity is heavily concentrated in China, followed by Japan and South Korea, highlighting Asia's central role in shaping both industrial and academic innovation ecosystems across membrane technologies.

7.4 Summary and Outlook

Polymer membrane technologies from 2015–2025 show steady maturation alongside rising strategic importance across water treatment, gas separation, chemical processing, and especially energy storage applications. Although overall publication activity remains stable, the strong patent share reflects sustained industrial investment and application driven innovation. Material trends show mature polymer systems such as fluoropolymers (PVDF, PTFE) and

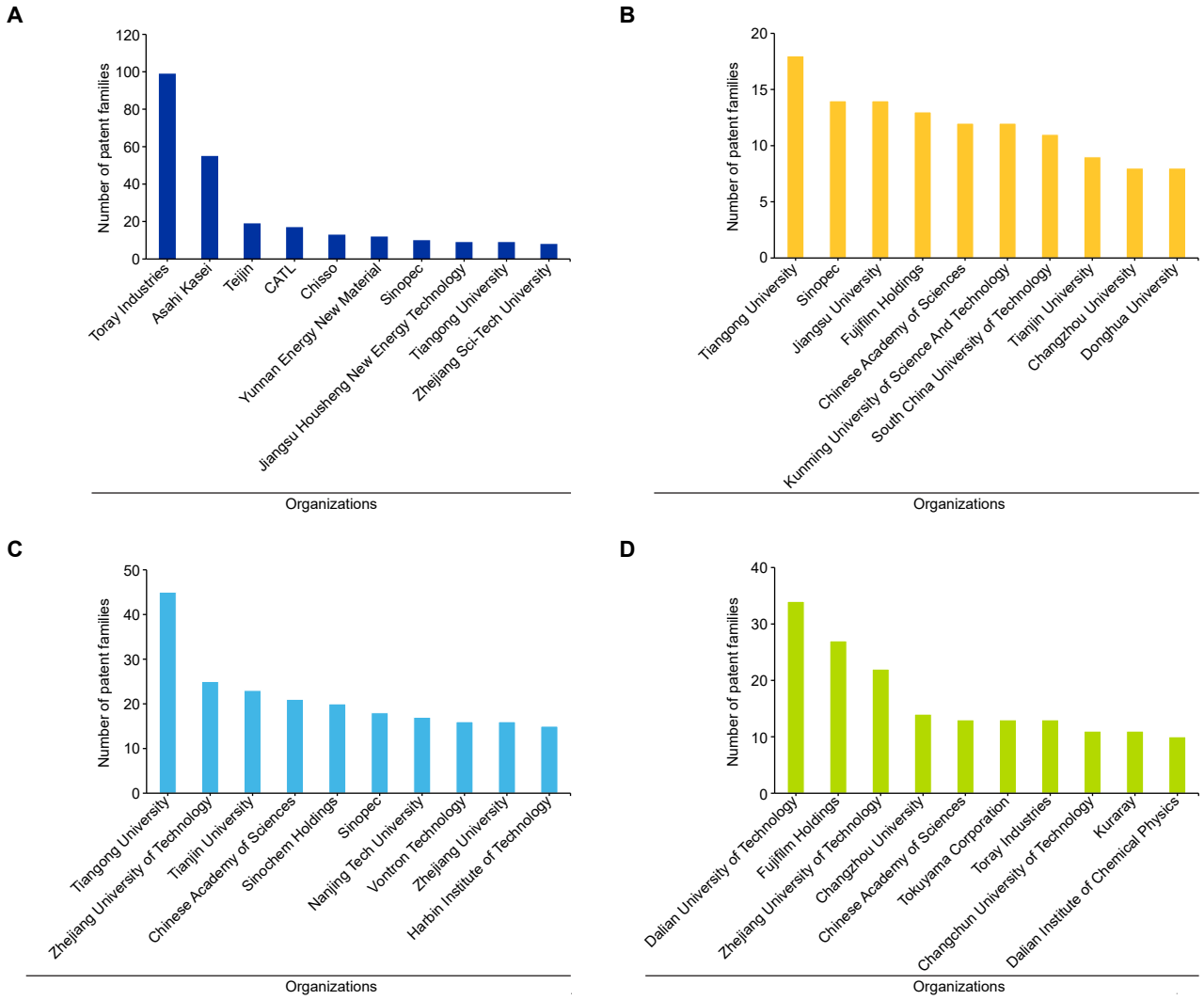


Figure 59. Leading organizations (corporate enterprises and academic institutions) involved in polymer membranes technologies across (**A**) microporous membranes; **B**) composite membranes; **C**) nanofiltration membranes; **D**) anion exchange membranes. Data includes patent publications for the period 2015-2025 from the CAS Content Collection.

polyolefins (PE, PP) coexisting with rapidly advancing functional materials including PVA, PEG, SBR, SBS, and bio based polymers. Current activity increasingly favors polymers that deliver improved mechanical stability, ionic conductivity, chemical resilience, and sustainability, supported by crosslinkers, antioxidants, and coupling agents that enhance durability under demanding operating conditions.

Among all application areas, secondary battery separators stand out due to accelerating electrification and rising demand for safer, higher-performance energy storage systems. This surge is driving intensive development of advanced polymer architectures and nanostructured membranes optimized for ion transport and thermal/electrochemical stability.

Composite, nanofiltration, and anion exchange membranes also show notable momentum, with the latter emerging as a particularly fast growing segment given its relevance to hydrogen production, fuel cells, and CO_2 electrolysis. Looking forward, polymer membranes are positioned for strong future growth as key enablers of clean energy systems, advanced separations, and more sustainable industrial processes. Development is expected to focus on high performance polymers, next generation membrane architectures, and modern manufacturing methods. Overall, the field is shifting from conventional separation uses toward high value, performance critical applications, reinforcing polymer membranes as foundational technologies for the coming decade.

8. Frontiers in polymer discovery

8.1 Next-Generation Polyesters

Polyester dominates global fiber productions, yet its fossil-based origins, microplastic pollution, and low textile-to-textile recycling rates have positioned it at the center of sustainability debates.[746] Today, scientific and industrial innovations are converging toward next-generation polyesters that are bio-sourced, biodegradable, and circular by design. Our NLP analysis of research trends (**Figures 14** and **15**) reveals a clear market transition. Emerging polyester chemistries show accelerating research momentum across diverse application areas, signaling both technological maturation and expanding commercial relevance. We further analyzed the trend of these NLP identified emerging polyesters for the 2020-2024 period (**Figure 60A** and **60B**).

PLA, although not a next-generation chemistry, provides a baseline for understanding how complementary bio-polyester technologies have evolved. It shows a steady growth across both journal and patent activity between the analysis period 2020-2024.

Polyethylene terephthalate glycol (PETG) demonstrates the most notable shift, rising from 7.4% to 44% of journal publications, even as its patent growth fluctuates, suggesting academic exploration of new applications rather than immediate commercialization. PBAT (10.5% to 32.3%), PBSA (12.4% to 27.6%) shows similarly impressive growth, while PBST also demonstrates research expansion up to 2023 followed by a subsequent decline. PHBV and PHBHHx demonstrate opposite pattern. Limited journal growth but sharp patent growth, indicating movement into applied development and commercialization. The surge in patents is driven by industry efforts to improve scalable fermentation processes, engineer microbial strains, reduce production costs, and develop application specific formulations such as blends, composites, and enhanced processing routes.[747]

Current research trend positions PETG as an enabling material for advanced manufacturing. Recent research explore PETG for high-performance composite matrix,[748] shape memory four-dimensional (4D) printing,[749] waste recycling[750] highlighting its potential in circular economy applications, including biodegradable modification and manufacturing process optimization. [751]

PBST research highlights its superior gas barrier performance and improved processing characteristics addressing earlier limitations of biodegradable materials.[752] PBAT research focuses on flexible packaging and agriculture (mulch films, soil biodegradation, and environmental compatibility).[753] PBSA demonstrates exceptional compatibility with PLA, addressing the inherent brittleness limitations of pure PLA systems[754] and showing compatibility with natural fillers.[755] Meanwhile PLA continues

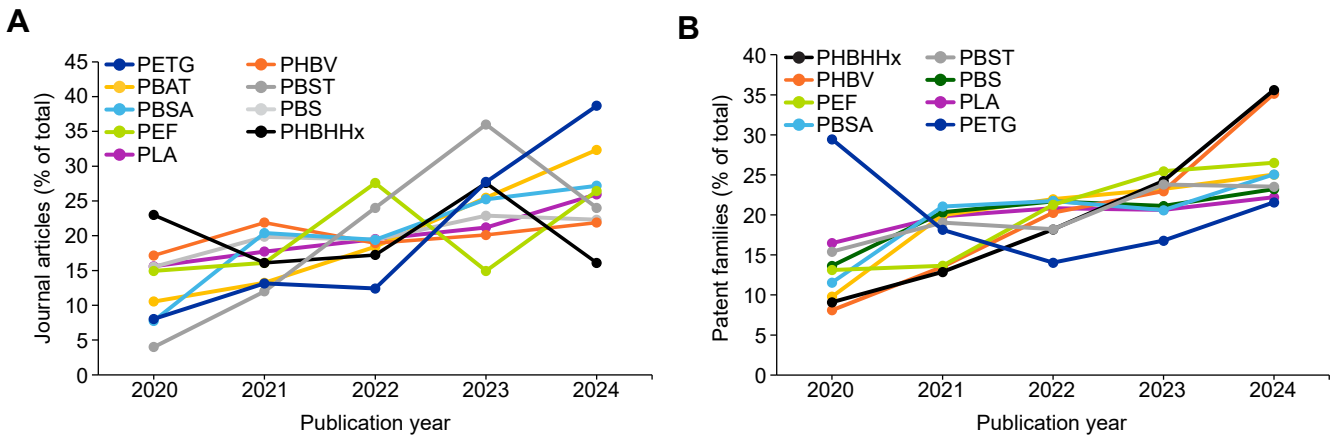


Figure 60. Publication trend of next-generation polyesters with respect to (**A**) journal articles and (**B**) patent families. Data includes journal articles and patent publications from the CAS Content Collection for the period 2020-2024.

to lead in digitally optimized additive manufacturing and multifunctional composites through enhanced interlayer bonding and waste-to-value filament innovations.[756, 757]

PHAs, particularly PHBV and PHBHHx, offer tunable mechanical performance and full compostability, though cost barriers currently limit widespread adoption.[747, 758] PHBV appears across high-strength blends, biomaterials, barrier films, and electrospun filters,[759] while PHBHHx, a more ductile PHA, helps address the inherent brittleness of PHBV and enables development of flexible, tough compostable films and molded parts suitable for consumer and medical packaging.[760] Together, these PHAs contribute to the compostable performance foundation enabling monomaterial designs where biodegradability, mechanical tuning, and leakage resistance are critical. PBS (biosuccinate routes) emerge as a thermoformable, compostable pillar for rigid packaging and molded goods where heat resistance and ductility must be balanced with industrial compostability.[761]

The emerging polyester patent landscape shows a clear concentration of activity in Asia, with Japan and China accounting for a significant share of global patent filings (**Figure 61**). This reflects the rapid scaling of sustainable polymer R&D in regions with strong manufacturing bases and established petrochemical sectors transitioning toward sustainability. CNPC holds a large and growing collection of patent families in this area. This trend underscores the wider petro to sustainable shift, with established producers expanding into biodegradable and bio based polyester technologies. At the same time, active patenting by Japanese precision chemical companies and innovators such as Mitsubishi Chemicals, Kaneka, and Kingfa Sci. and Tech. suggests that the technology is moving steadily from research into commercial deployment pathways. Patent activity from Europe and North America remains present but less concentrated, indicating different regional innovation strategies.

This diversified polyester ecosystem represents a fundamental shift from the historical dominance of single-polymer solutions toward

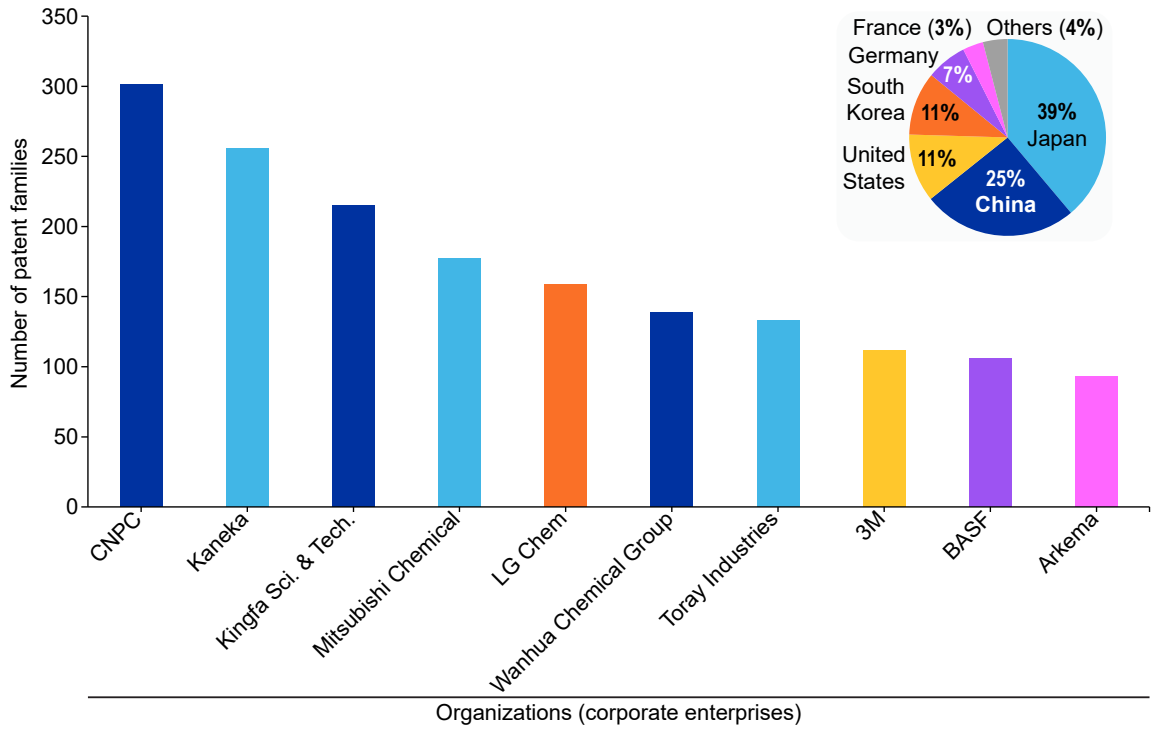


Figure 61. Leading organizations (corporate enterprises) in next-generation polyester landscape. Pie-chart represents their geographic distribution of the organizations. Data includes journal articles and patent publications from the CAS Content Collection for the period 2020-2024.

application-tailored material strategies that integrate performance requirements with end-of-life considerations. The emerging landscape suggests that successful market penetration will depend not only on individual polymer performance but on the development of compatible processing infrastructure, standardized compostability protocols, and supply chain integration that can support the transition from research innovation to industrial scale deployment. As regulatory frameworks increasingly favor circular design principles, this next-generation polyester portfolio positions the industry to move beyond simple bio-based substitution toward genuinely sustainable material systems that can meet both technical specifications and environmental imperatives across diverse market sectors.

8.2 High Performance Elastomers

NLP analysis of polymer-related patents and journal publications from 2020-2024 reveals high performance elastomers as a rapidly emerging research domain, characterized by convergent innovation across multiple technological frontiers. This comprehensive field encompasses smart responsive materials, enhanced processing platforms, and application-specific performance optimization, representing a paradigm shift from conventional elastomer development toward multifunctional, adaptive polymer systems. The emerging high performance elastomer domain spans five critical technology clusters: liquid crystal elastomers (LCEs) enabling programmable shape-changing materials; conductive elastomers bridging mechanical flexibility with electrical functionality; thermoplastic elastomers (TPEs) providing recyclable alternatives to thermoset rubbers; specialty synthetic rubbers offering enhanced chemical and thermal resistance; and bio-based elastomers addressing sustainability requirements while maintaining performance standards.

This technological convergence reflects industry demands for materials that simultaneously address mechanical performance, environmental sustainability, processing efficiency, and emerging applications in soft robotics, wearable electronics, and autonomous systems. The NLP-identified terms reveal a field transitioning from empirical rubber compounding toward design of elastomeric materials with predictable, tunable properties.

Figure 62 presents the publication trends of emerging elastomers in journal and patents. Conductive elastomers, LCEs, and thermoplastic polyamide elastomers (TPAEs) are the emerging materials in journal articles (**Figure 62A**). LCEs represent the most scientifically significant emerging technology, combining liquid crystalline order with elastomeric networks to create programmable actuator materials.[762] These systems exhibit reversible shape changes in response to thermal, optical, or electrical stimuli, with applications in soft robotics, 3D printing, and biomedical devices.[763] LCEs function through coupling between liquid crystal director orientation and mechanical

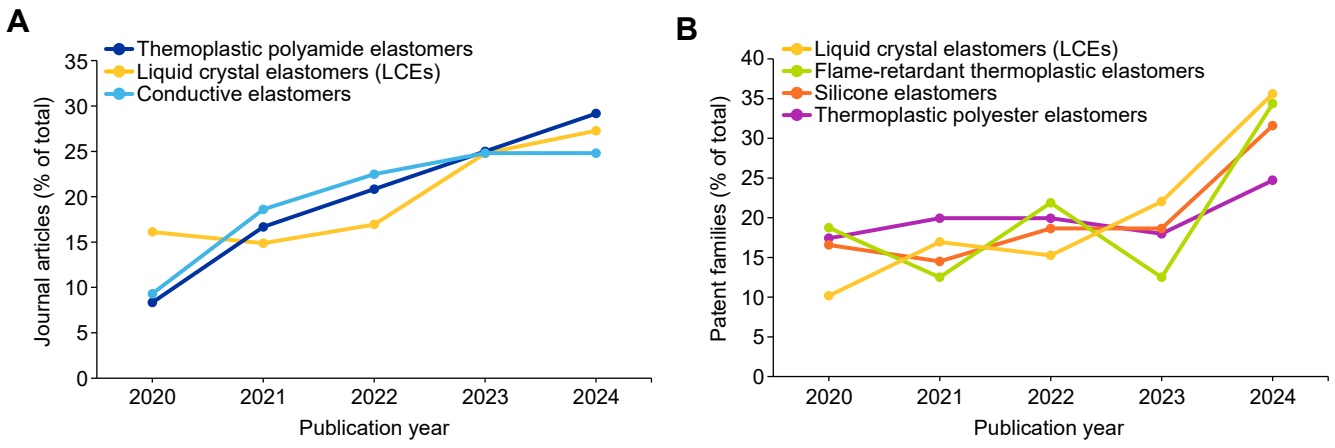


Figure 62. Publication trends for the emerging elastomers in journals and patents during the period 2020-2024.

deformation, enabling materials that can perform complex motions including bending, twisting, and oscillation. Conductive elastomers emerge as critical materials for flexible electronics and soft robotics applications, where mechanical deformation must be accompanied by maintained or controlled electrical conductivity.[764] These materials typically incorporate conductive fillers (carbon nanotubes, graphene, metal particles) within elastomeric matrices, creating strain-sensitive electrical networks.[765] The percolation behavior of conductive networks under mechanical deformation enables development of pressure sensors, strain gauges, and flexible circuits that maintain functionality during large deformations exceeding 100% strain.[766] TPAEs represent advanced segmented copolymers combining polyamide hard segments with flexible soft segments, providing high-temperature elastomeric performance with thermoplastic processability.[767] These materials offer superior mechanical properties at elevated temperatures compared to conventional TPEs, with applications in automotive under-hood components and industrial sealing systems.[768] The hydrogen bonding in polyamide segments creates physical crosslinks that provide elastomeric behavior while remaining thermally reversible for recycling and reprocessing.

The emerging elastomers in patent families are flame-retardant thermoplastic elastomer, LCEs, silicon elastomer, and thermoplastic polyester elastomer (TPEEs) (**Figure 62B**). Flame-retardant thermoplastic elastomers address critical safety requirements in transportation, construction, and electrical applications. [769] These materials incorporate flame-retardant additives or inherently flame-resistant polymer structures while maintaining elastomeric properties and thermoplastic processability. Innovation focuses on halogen-free flame retardancy through phosphorus-based additives, metal hydroxides, or inherently flame-resistant polymer backbones that meet stringent fire safety standards without environmental concerns associated with halogenated compounds. Silicone Elastomers continue evolving toward specialized applications requiring extreme performance conditions. Advanced formulations provide biocompatibility for medical implants, thermal stability exceeding 200°C for aerospace applications, and optical transparency for LED encapsulation.[770, 771] Patent activity focuses on novel crosslinking chemistries, functional silicone modifications, and processing technologies that enable complex geometries and multi-material integration. TPEEs represent mature technology experiencing renewed innovation through bio-based feedstocks and enhanced performance formulations.[772] These segmented copolymers combine crystalline polyester hard segments with flexible polyether or polyester soft segments, providing chemical resistance and high-temperature performance superior to conventional TPEs.[773] Commercial development emphasizes automotive applications where TPEEs replace thermoset rubbers in fuel system components, providing recyclability advantages while maintaining chemical compatibility with modern fuel formulations.[774]

In summary, the trends in high performance elastomers reflect industry demands for materials simultaneously addressing mechanical performance, sustainability, processing efficiency, and emerging applications in soft robotics, wearable electronics, and autonomous systems. This technological evolution positions high performance elastomers for mainstream industrial adoption across traditional industry boundaries.

8.3 Conductive polymers

NLP analysis of the polymer data further revealed a marked attention towards conductive polymers in both journal articles (**Figure 14**) and patents (**Figure 16**), highlighting them as an emerging area of technological and scientific momentum. While conductive polymers have long been recognized for their unique combination of polymeric flexibility and electronic functionality, the recent surge in conductive elastomers, conductive adhesives, conductive polymer composites, and conductive polymer electrolytes suggests a shift beyond foundational materials toward application-oriented and hybrid conductive systems. We expanded our analysis to explore how the use of these conductive systems has evolved in both journal publications

and patents. **Figure 63** shows a clear emergence of these advanced conductive materials during 2020-2024, revealing a significant shift toward multifunctional materials that combine electrical conductivity with mechanical or adhesive properties, addressing critical needs in flexible electronics, energy storage, and advanced manufacturing applications.

Conductive adhesives represent a rapidly evolving field where academic research focuses on developing materials that can replace traditional solder connections while enabling low-temperature processing and flexible substrate compatibility.[775] Journal articles emphasize improving thermal stability and conductivity using fillers like silver, MXenes, and carbon nanotubes, while also developing thermal adhesives that pair strong bonding with effective heat management for electronic packaging.[776, 777] Conductive adhesives are additionally explored for flexible and stretchable electronics, where maintaining conductivity under deformation is essential for application in wearables, soft robotics, and flexible sensors.[778]

In patents, conductive adhesives are positioned for immediate commercial use in LED packaging, battery components, and photovoltaics.[779, 780] In LEDs, they enable low-temperature electrical bonding with efficient heat dissipation and in batteries, they bond electrodes while lowering thermal stress and internal resistance.[781, 782] Additionally, patents emphasize heat-resistant adhesives indicating industrial focus on materials that maintain both adhesive strength and electrical conductivity at elevated operating temperatures, critical for automotive and power electronics applications.[783] Overall, patents underscore conductive adhesives as practical solutions that enhance performance across diverse devices and journal articles are focused on improving and developing them for advanced emerging applications.

Conductive elastomers show consistent growth over the period, in both journal articles and patents, indicating sustained academic and industrial interest in this field. The prominence of conductive elastomers reflects a growing push toward stretchable, and wearable electronics soft robotics applications, as they combine electrical conductivity with high elasticity.[176, 784] They are widely used in soft sensors and actuators, where their resistance changes with strain or pressure, enabling applications in health monitoring, human–machine interfaces, and prosthetic sensing.[785] Moreover, their growth also implies that researchers and industry alike are moving from rigid conductive frameworks to highly compliant architectures capable of sustaining mechanical stress without compromising electrical performance.

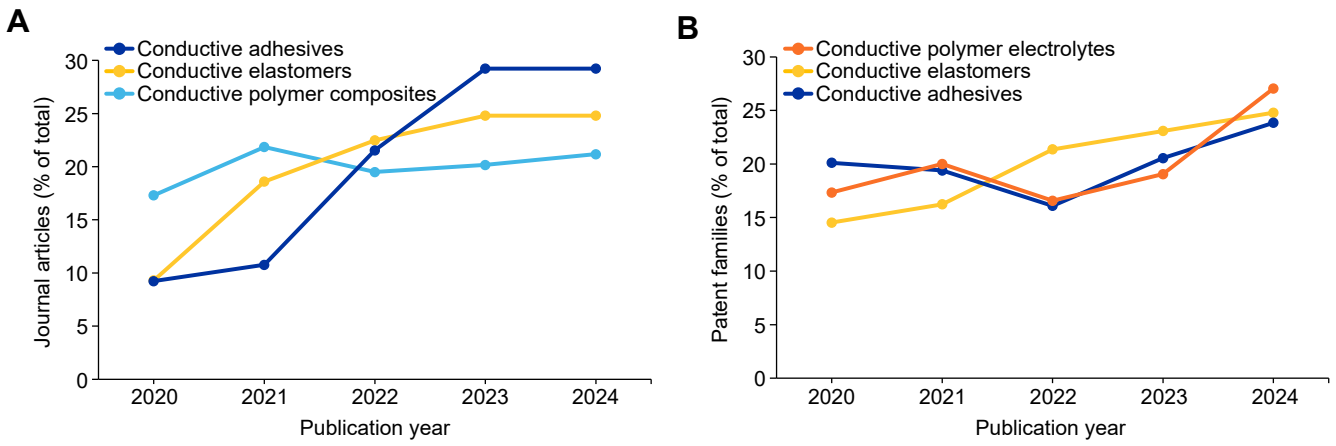


Figure 63. Publication trends across (**A**) journal articles and (**B**) patent families for emerging conductive polymer systems for the period 2020–2024 from the CAS Content Collection.

Conductive polymer composites show a relatively stable yet gently rising research trajectory into 2024, reflecting continued efforts to enhance conductivity through filler engineering. The research momentum is driven by the versatility of these composites to support applications in e-skin, wearable electronics, and human motion detection.[786] Their tunable dielectric and stimuli-responsive properties also enable roles in EMI shielding, sensing platforms, and soft-robotic actuation.[787] As research continues to expand the design space for advanced composite architectures, a corresponding uptick in patent activity may follow as new material combinations and processing pathways reach technological relevance.

Conductive polymer electrolytes show the fastest growing field in the patent landscape reflecting urgent commercial needs for solid-state batteries and safer energy storage systems. Patents likely focus on polymer electrolytes that combine high ionic conductivity with mechanical stability and wide electrochemical windows, targeting applications in next-generation lithium batteries, supercapacitors, and electrochromic devices.[788,789] These materials address critical safety concerns in electric vehicles while enabling new form factors for portable electronics. The surge in patent activity indicates successful translation of fundamental research into commercially viable formulations that can be manufactured at scale while meeting stringent performance requirements for thermal stability, cycle life, and safety.

Together, these systems reveal a broader shift in the conductive polymer landscape—from isolated study of intrinsically conductive backbones toward system-level design philosophies, where conductivity is integrated with mechanical compliance, adhesion, structural reinforcement, or ionic mobility. The convergence of these directions signals a more mature and application-driven research ecosystem, positioning conductive polymers as versatile enablers across electronics, energy, and emerging multifunctional technologies.

8.4 Dynamic polymer networks

NLP analysis of the polymer data reveals that dynamic polymer networks (DPNs) form a distinctly emerging research topic in journal publications (**Figure 14**), with no parallel rise in patent activity. This asymmetry indicates that DPNs are currently in a science-driven, concept-development phase, where researchers are actively exploring new chemistries, mechanisms, and design rules, while industry adoption remains limited.

DPNs depart from the classical paradigm of permanent, inert crosslinked polymers and instead incorporate reversible or exchangeable interactions that enable functions such as self-healing, stress relaxation, welding, reprocessing, shape reconfiguration, and recyclability.[790] Their growing prominence in academic literature reflects broader motivations in polymer science, particularly sustainability, circular material design, and demand for damage-tolerant, adaptive materials, yet the lack of patent growth suggests that these ideas have not yet translated into mature manufacturing practices or robust industrial formulations. In other words, the field is expanding intellectually, but commercial pathways remain in incubation.

Within the DPN landscape, the most widely discussed category is covalent adaptable networks (CANs), which entwines the mechanical robustness of covalently crosslinked polymers with the capacity to reorganize their network topology under external stimuli.[791] CANs have gained increasing attention in the literature because they promise reprocessable thermosets—a long-sought challenge in polymer materials.[792]

CANs are further divided into two major classes—vitrimers and dissociative covalent networks—each with distinct dynamics and practical limitations. Vitrimers enable flow through associative exchange while maintaining crosslink density, but challenges such as catalyst complexity, moisture sensitivity, and performance drift during reprocessing still hinder

industrial adoption.[793, 794] Dissociative covalent networks offer responsive behavior through dissociative exchange, yet their dissociation-driven softening can reduce mechanical integrity, limiting use in load-bearing composites, coatings, and adhesives.[795, 796]

Beyond CANs, supramolecular polymer networks form the second major class of dynamic systems. These networks rely on reversible non-covalent interactions such as hydrogen bonding, ionic clusters, host–guest complexes, π-interactions, or metal–ligand coordination.[797] However, supramolecular systems face constraints in creep resistance, environmental stability, moisture sensitivity, and long-term durability, all of which hinder industrialization.[798]

We further analyzed the publication trends across these different types of dynamic systems in our data (**Figure 64**). These trends reveal a clear divergence in research momentum, with vitrimers emerging as the fastest-growing and most rapidly consolidating polymer network. This steep rise reflects the field's shifting focus toward reprocessable thermosets, driven by industrial demand for recyclable composites, reworkable coatings, and sustainable high-performance materials.[799] Moreover, this steep growth likely corresponds to both diversification of vitrimer chemistries (e.g., transesterification, imine exchange, diketoenamine exchange) and increased efforts to address long-standing challenges.[800, 801]

In contrast, dissociative covalent networks show a more moderate but steady rise. Their growth trajectory suggests renewed interest in mild-condition self-healing systems. However, their dissociative nature and weaker mechanical stability likely constrain their expansion relative to vitrimer systems.[796] Supramolecular polymer networks show the slowest rate of increase. This trend is consistent with their more mature scientific foundation and with practical limitations such as creep sensitivity, environmental instability, and weaker load-bearing performance compared to covalent networks.[798] The gradual rise suggests ongoing application-driven research in self-healing coatings, stretchable electronics, and biomedical materials rather than fundamental breakthroughs.

Overall, current academic literature is focused on identifying chemistries with improved stability and cycling endurance, but widespread commercialization will require more robust performance and compatibility with fillers and reinforcements.

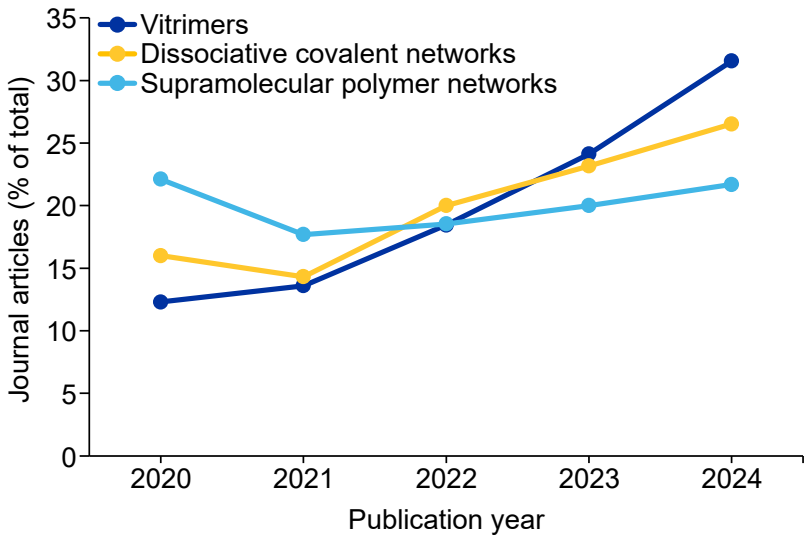


Figure 64. Publication trends for journal articles for emerging dynamic polymer network types during the period 2020–2024 from the CAS Content Collection.

8.5 Advanced Engineering Materials

NLP analysis of polymer-related patents and journal publications from 2020-2024 identifies advanced engineering polymer materials (AEMs) as a rapidly emerging research domain. AEMs are materials used in high-performance applications that require exceptional mechanical, thermal, and chemical properties in areas such as aerospace, automotive, electronics, and industrial applications. The advanced engineering polymer domain encompasses several critical technology clusters: long-chain polyamides offering enhanced mechanical properties and processing advantages; aramid nanofibers (ANFs) providing ultra-high strength reinforcement; bio-based engineering polymers combining sustainability with performance; specialty polyesters addressing specific application requirements; and high-performance thermoplastics enabling processing flexibility while maintaining superior properties.

Figure 65 presents the publication trends for emerging materials in journals and patents. Aramid, PA56, PETG, and poly(m-phenylene isophthalamide) (PMIA) are the emerging materials in journal articles (**Figure 65A**). Aramids represent the most scientifically significant emerging technology in academic research, particularly focusing on ANFs as next-generation reinforcement materials. These ultra-high strength fibers, derived from conventional aramid polymers through controlled defibrillation processes, provide exceptional mechanical reinforcement at nanoscale dimensions. ANFs function as multifunctional additives in composite systems, providing not only mechanical reinforcement but also thermal management, electrical insulation, and barrier properties.[802] Research emphasizes developing scalable production methods for ANFs and understanding their dispersion behavior in various polymer matrices to optimize composite performance. PMIA emerges as a high-temperature aramid offering superior thermal stability and flame resistance compared to conventional engineering plastics.[803, 804] PMIA's meta-linked aromatic structure provides inherent flame retardancy without additives while maintaining processability advantages over para-aramids like Kevlar. Academic research focuses on developing processing technologies for PMIA, understanding degradation mechanisms at elevated temperatures, and exploring applications in aerospace and electronics where flame resistance is critical. PA 56 emerges as a critical bio-based engineering polyamide combining renewable feedstock utilization with enhanced performance characteristics. Derived from pentamethylene diamine (bio-based) and adipic acid, PA 56 provides superior dimensional stability and lower moisture absorption compared to conventional PA 6 and polyamide 66 (PA 66).[805] The polymer's balanced crystallization behavior enables processing advantages while maintaining mechanical

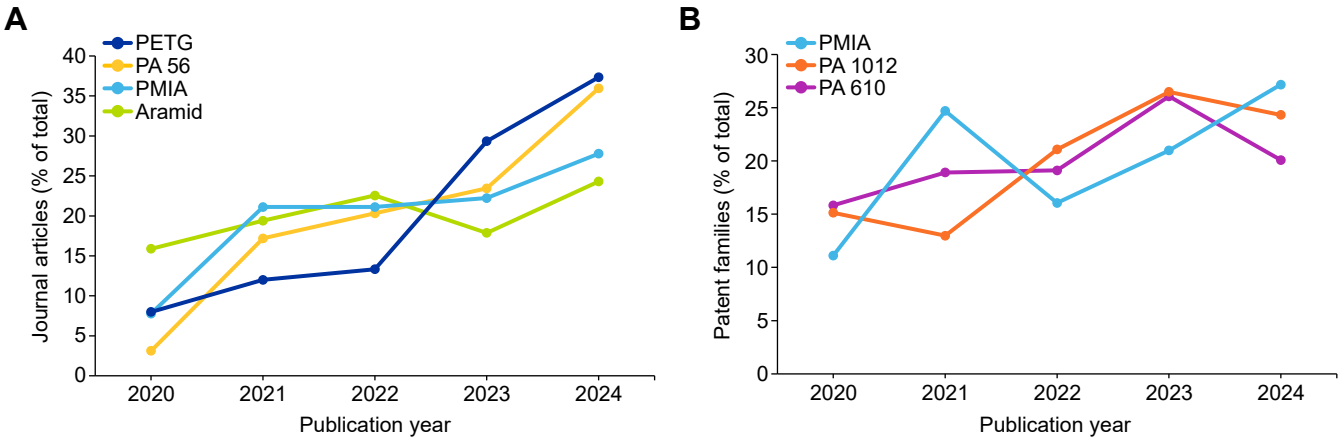


Figure 65. Publication trends for the emerging advanced engineering materials in (**A**) journals and (**B**) patents during the period 2020-2024.

properties suitable for automotive and industrial applications. Academic research focuses on optimizing synthesis pathways, understanding structure-property relationships, and developing application-specific grades. PETG represents advanced amorphous polyester technology providing exceptional clarity, chemical resistance, and processability. Unlike crystalline PET, PETG's amorphous structure enables thermoforming and injection molding applications requiring optical clarity and impact resistance.[806] Research emphasizes understanding the relationship between glycol modification levels and resulting properties, developing recycling pathways for PETG waste streams, and optimizing processing conditions for complex geometries.

Polyamide 610 (PA 610), Polyamide 1012 (PA 1012), and PMIA are the emerging materials in patent families (**Figure 65B**). PA 610 demonstrates strong commercial development as a bio-based long-chain polyamide offering enhanced performance characteristics. Derived from hexamethylene diamine and sebacic acid (castor oil-based), PA 610 provides lower moisture absorption, improved dimensional stability, and enhanced chemical resistance compared to conventional short-chain polyamides.[807] Patent activity focuses on automotive fuel system applications where PA 610's chemical resistance to modern fuel formulations (including ethanol blends) provides advantages over PA6 and PA 66 while meeting sustainability requirements.[808] PA 1012 represents advanced long-chain polyamide technology providing exceptional flexibility and impact resistance while maintaining engineering plastic performance levels. The longer methylene sequences in PA 1012 reduce crystallinity and glass transition temperature, enabling applications requiring low-temperature flexibility without compromising mechanical strength.[809] Commercial development emphasizes applications in harsh environments where conventional engineering plastics become brittle, including automotive exterior components and industrial equipment exposed to temperature cycling. PMIA appears in both journal and patent landscapes, indicating successful research-to-commercialization transition. Patent activity focuses on processing technologies, fiber spinning methods, and application-specific formulations for industries requiring high-temperature performance and flame resistance. Commercial applications include aerospace interior components, electrical insulation systems, and protective equipment where PMIA's combination of processability and performance provides advantages over traditional thermoset materials.[810, 811]

In summary, the advanced engineering polymer materials field demonstrates remarkable convergence between fundamental research advances and commercial innovation priorities, with bio-based long-chain polyamides and aramid nanofibers representing the most significant emerging technologies. The simultaneous emergence of these materials in both academic and patent literature indicates successful technology transfer and commercial viability.

8.6 Hyperbranched Polymeric Materials

NLP analysis shows the field of hyperbranched polymers is growing at a rate of +10% in patents between 2020-2024, showing a strong interest in commercial research (**Figure 16**). These are a unique class of macromolecules characterized by their highly branched, three-dimensional tree-like architecture that differs significantly from conventional linear polymer chains.[812] Unlike traditional polymers that grow in a linear fashion, hyperbranched polymers contain numerous branching points throughout their structure, creating a dense, globular morphology with a multitude of functional end groups.[813] This distinctive architecture endows them with exceptional properties including low solution viscosity despite high molecular weight and a high concentration of reactive terminal groups that can be modified for specific applications. Their unique combination of processability, functionality, and performance characteristics has made hyperbranched polymers increasingly attractive for applications ranging from semiconductors[814] to energy storage systems.[815]

Figure 66A shows a clear upward rise in patent families for hyperbranched polymeric materials from 2015 to 2025, reflecting growing commercial

interest and the technological maturation of these application ready architectures. This trend aligns with our NLP findings, which identified hyperbranched polymers as an emerging topic within the broader polymer landscape, underscoring their transition from a research focused area into a strategically important platform for various applications. We further examined different hyperbranched polymer classes identified as high growth areas in our NLP analysis (**Figure 16**)—specifically polyesters, polysiloxanes, polyepoxides, and polyamides—as shown in **Figure 66B**.

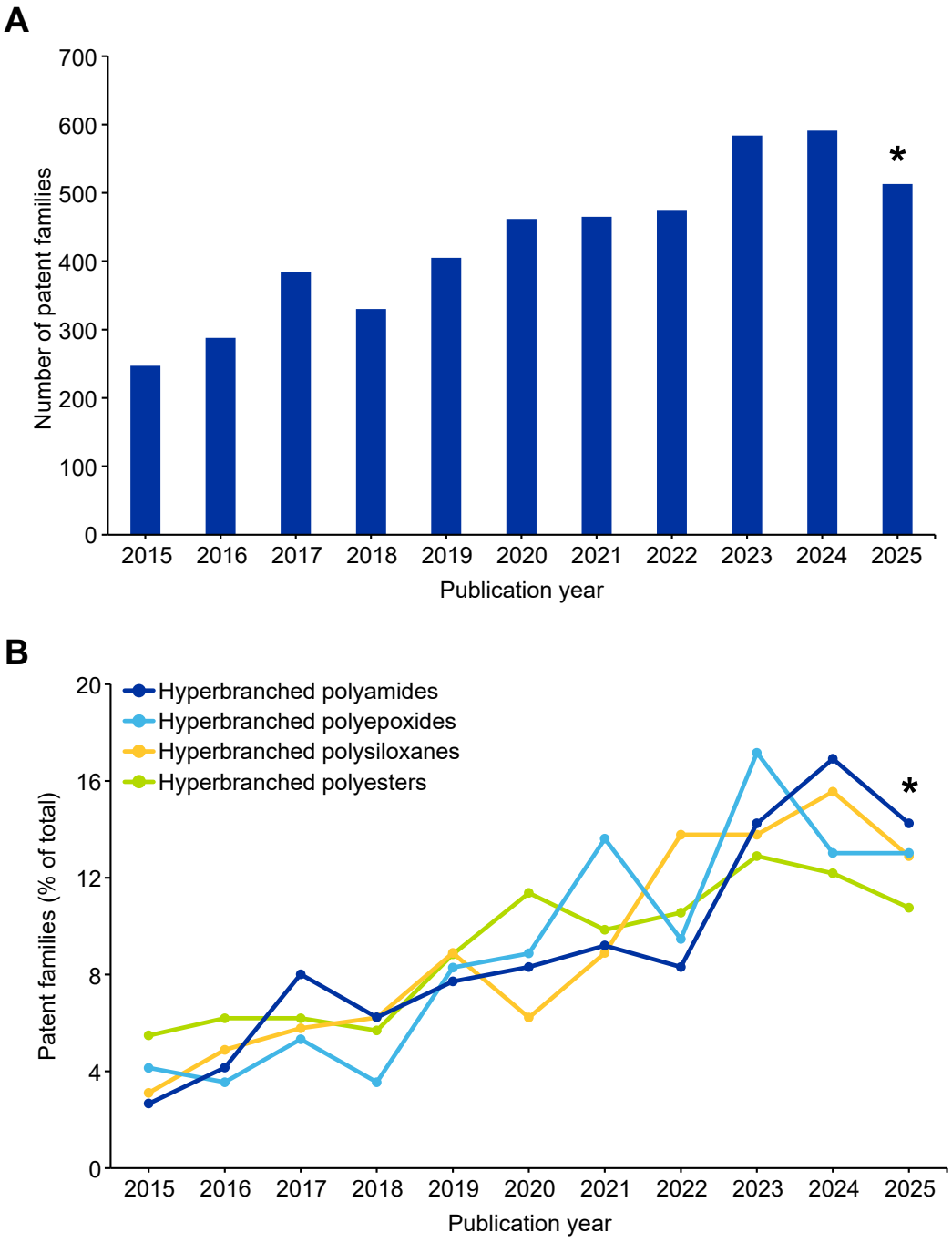


Figure 66. (**A**) Patent publication trends of hyperbranched polymeric materials and (**B**) relative patent publication trends of specific classes of hyperbranched polymeric materials, namely polyesters, polysiloxanes, polyepoxides, and polyamides. *Data only for the months January to November in 2025.

This rising patent activity in hyperbranched polyesters, polysiloxanes, polyepoxides, and polyamides reflects their expanding roles as functional, application-ready materials with chemical architectures well-suited to emerging industrial needs. Hyperbranched polyesters are gaining traction due to their biodegradability, and compatibility with nanomaterial formulations, making them attractive for sustainable, biomedical, and high-performance applications.[816, 817] Hyperbranched polysiloxanes exhibit exceptional thermal stability, flexibility, fluorescence, and surface-modification potential, which aligns with the growing demand for advanced coatings, biosensors, drug delivery, bioimaging, and chemical detection.

Hyperbranched polyepoxides offer high crosslinking density and excellent mechanical and chemical resistance, supporting their rapid adoption in adhesives, composites, and protective coatings.[818, 819] Finally, hyperbranched polyamides benefit from strong mechanical strength, solvent resistance, and functionalizability, making them increasingly important in membranes, and barrier materials.[820] The growth across all four classes reflects a broader shift toward polymers with high functionality, structural versatility, and compatibility with next-generation technologies.

8.7 Framework Materials

Framework materials represent a revolutionary class of crystalline, highly porous materials that have transformed materials science through their structural versatility and tunable properties[821] and have shown to be growing by >2X average fold increase between 2020-2024 from our NLP analysis in **Figure 12**. MOFs (**Figures 11** and **Figure 13**) consist of metal ions or clusters (nodes) connected by organic ligands (linkers), creating three-dimensional networks with extraordinarily high surface areas (often exceeding 1000 m^2/g) and precisely controllable pore sizes.[822] COFs (**Figures 11** and **Figure 13**) are purely organic crystalline materials where building blocks are connected through strong covalent bonds, offering exceptional chemical stability, permanent porosity, and the ability to incorporate functional groups throughout their structure.[821] Zeolitic imidazolate frameworks (ZIFs) represent a specialized subset of MOFs that combine metal nodes (typically zinc or cobalt) with imidazolate linkers to create structures that mimic the topology of zeolites while maintaining the chemical tunability of MOFs, resulting in materials with exceptional thermal and chemical properties.[823] Hydrogen-bonded organic frameworks (HOFs) are constructed through weaker but more dynamic hydrogen bonding interactions, allowing for more flexible and responsive structures.[824] These framework materials collectively offer unprecedented control over porosity, surface chemistry, and functionality, making them invaluable for applications such as gas storage, energy storage, separation and catalysis, with their modular design enables tailored properties for specific applications through a rational selection of building blocks.[825,826]

Framework materials can be strategically integrated with polymers to create advanced composite materials that combine the processability and mechanical properties of polymers with the exceptional porosity and functionality of framework structures.[827] These hybrid systems are typically formed by dispersing framework particles (MOFs, COFs, HOFs, or ZIFs) within polymer matrices such as polysulfone, polyimide, or polysiloxane. The framework materials act as selective fillers that can dramatically enhance gas separation performance, catalytic activity, or sensing capabilities while the polymer provides structural integrity, flexibility, and ease of processing into films, fibers, or complex shapes.[828]

The remarkable growth in patent publication related to polymeric framework materials from 2015 to 2025 is shown in **Figure 67**. The overall publication activity is showing a steady positive increase to 2023, which then accelerates, with publications peaking at over 700 patents by 2024-2025. MOFs dominated the early research landscape and maintained a substantial presence throughout the study period. However, the most striking observation is the explosive growth of COFs, which emerged as a minor component in early years but became the primary driver of

recent growth, particularly from 2022 onwards. ZIFs maintained a consistent but relatively modest contribution across all years, while HOFs remained the smallest growing research segment. The data suggests that while the field of polymeric framework materials is experiencing unprecedented expansion, COFs have become the dominant research focus, fundamentally shifting the landscape and accounts for the publication increase in recent years.

8.8 Actinic Ray-Sensitive Polymers

Actinic radiation refers to high-energy ultraviolet and short-wavelength visible light capable of initiating photochemical reactions. In semiconductor lithography, actinic ray sensitive polymers serve as binder resins in chemically amplified resists (CARs). These materials operate through a well-established mechanism involving exposure to actinic radiation, followed by photoacid generator (PAG) activation, acid-catalyzed deprotection or chain scission, and subsequent polarity changes that enable selective dissolution.[829] The performance of these resist systems depends on the interplay between photoacid generation and diffusion, polymer molecular architecture, and developer solution interactions, which collectively determine key lithographic parameters including sensitivity, resolution, and stochastic noise characteristics.[830] Notably, our patent NLP analysis (**Figure 16**) reveals that actinic ray sensitive polymers, though still a relatively small research segment by volume, exhibit a strong growth rate (>2), indicating rising innovation activity and renewed technological interest in next generation resist materials. This growth trend reflects the industry's ongoing efforts to develop next-generation lithographic materials capable of supporting continued semiconductor device scaling and emerging patterning challenges.

Figure 68 highlights a growing momentum in actinic ray sensitive polymer patent filings. Interestingly, only two Japanese organizations, Fujifilm Holdings and Artience, account for the entirety of patents in this space. The analysis reveals that Fujifilm Holdings' actinic-ray-sensitive polymer innovation, delivered through a comprehensive materials platform engineered for sub-25 nm extreme ultra-violet (EUV) lithography.[831, 832] Rather than developing

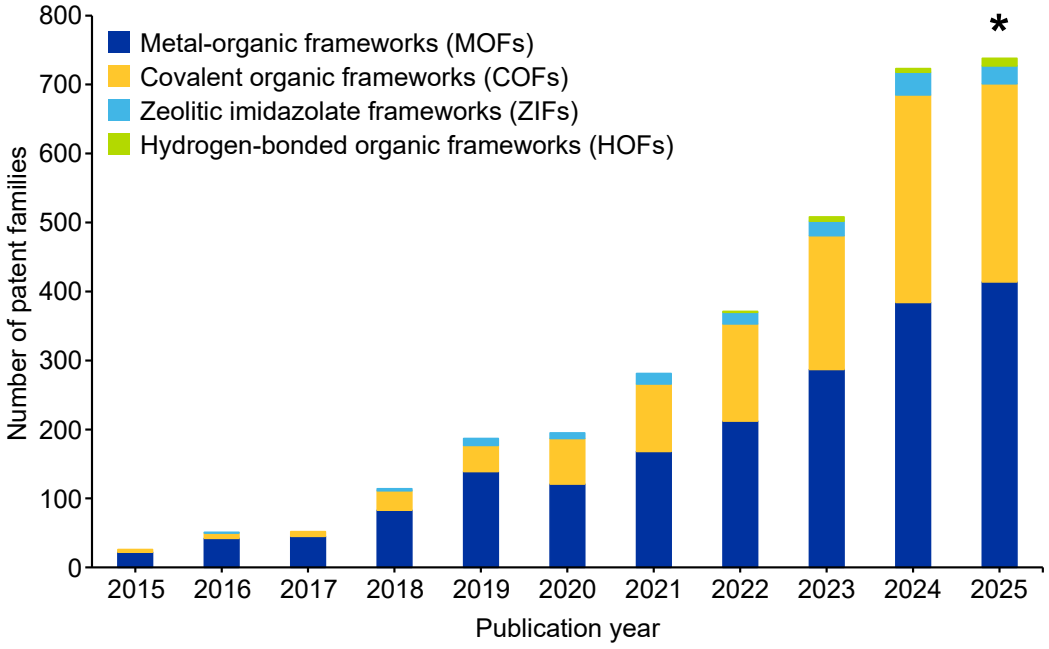


Figure 67. Patent publication trends of specific classes of framework materials. *Data only for the months January to November in 2025.

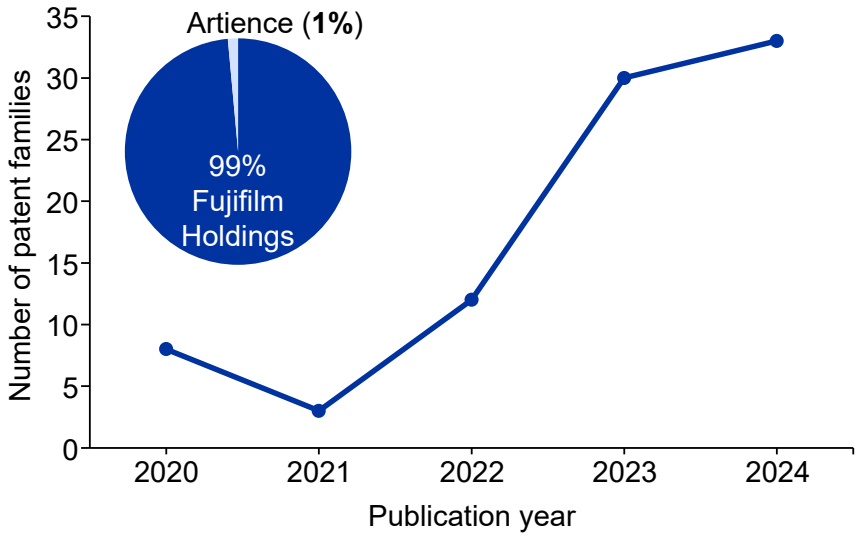


Figure 68. Publication trend of actinic-ray sensitive polymers. The inset pie chart shows the organizational (corporate enterprises) distribution of patent families. Data includes patent publications from the CAS Content Collection for the period 2020-2024.

isolated inventions, Fujifilm's approach integrates PAGs, polymer architectures, and processing conditions as an interdependent system targeting the fundamental resolution-line roughness-sensitivity trade-off. Their chemical architecture combines for example, engineered sulfonium/iodonium salt PAGs with specialized polymer backbones including fluorinated aromatics for diffusion control.[833] It also includes silicon-containing frameworks for etch resistance[834] and main-chain scission polymers for high sensitivity,[835] complemented by precision additives like boron compounds and metal sensitizers that fine-tune acid lifetime and EUV absorption.[836] Processing is treated as co-engineered chemistry, using organic developers (butyl acetate blends) matched to engineered polarity changes, double development sequences for resolution control, and protective upper layer films.

This system-level approach demonstrates that future EUV advances will require coordinated optimization across the entire resist ecosystem rather than breakthroughs in any single-component. It also positions the platform for sub-20nm high numerical aperture (NA) EUV requirements, where photon-stochastic limits demand precisely controlled chemical responses achieved through integrated materials-process co-design.

9. Conclusion

9.1 Synthesis of Global Polymer Innovation Landscape

This comprehensive analysis of nearly one million polymer-related publications from 2015-2025 reveals a field experiencing unprecedented transformation. Through systematic examination of bibliometric data, NLP-derived insights, and CAS-indexed concepts, we have mapped the evolution of polymer science from a materials-focused discipline to an integrated solutions science addressing critical global challenges. The most profound finding is the fundamental geographic redistribution of innovation capacity. China's emergence as the dominant force, contributing 40% of journal articles and 56% of patent families, represents more than a quantitative shift. It signals a new innovation paradigm where Asian institutions, particularly Chinese state-owned enterprises and universities, drive fundamental research and commercial development. This concentration, coupled with Japan's exceptional efficiency in converting research to high-value patents and South Korea's focused innovation in electronics and chemicals, has established Asia-Pacific as the global center of polymer innovation, controlling 82% of flexible electronics patents and similar proportions across other strategic domains.

9.2 Convergent Themes and Technological Evolution

Our multi-dimensional analysis reveals transformative themes reshaping polymer science:

Integration of Multifunctionality: The field has evolved beyond single-property optimization toward materials that address multiple performance requirements. This is exemplified across all examined domains. Polymers in energy storage must balance ionic conductivity with mechanical stability and processability; flexible electronic materials integrate structural support with electrical functionality and environmental protection; membrane technologies combine selectivity with durability and scalability. This convergence toward multifunctional platforms represents a fundamental shift in material design philosophy.

Sustainability as Performance Driver: The historical dichotomy between environmental compatibility and functional performance has dissolved. Sustainable polymers now demonstrate 190% growth in journal publications with parallel patent expansion, indicating successful commercialization. Materials like PLA, PBAT, and bio-based polyamides compete on performance metrics rather than environmental benefits alone. The emergence of synthetic biology platforms producing drop-in monomers and direct microbial polymer synthesis further accelerates this transition, with lactic acid and succinic acid platforms achieving industrial maturity.

Manufacturing-Driven Innovation: Processing considerations increasingly dictate material selection and development priorities. This is evident in the prominence of scalable processing methods in patent landscapes, the emphasis on aqueous processing in battery applications, and the critical role of solution processability in flexible electronics. The integration of additive manufacturing with polymer innovation exemplifies how processing technologies shape material development trajectories.

9.3 Application-Specific Insights and Opportunities

9.3.1.Energy Storage Systems

Polymers have emerged as critical functional components rather than passive materials, with batteries dominating 75% of energy storage patents. The field shows clear material-application alignment: fluoropolymers lead in battery separators and binders; natural polymers like CMC drive sustainable electrode technologies; solid-state batteries diverge between academic focus on PEG-based electrolytes and industrial emphasis on processable fluoropolymers. The growth in zinc-ion technologies and emerging sodium-ion systems indicate diversification beyond lithium-ion, creating opportunities for specialized polymer electrolytes and separators.

Key Strategic Insight: The extreme divergence between academic research (exploring novel PEG-based solid electrolytes) and industrial patents (optimizing established fluoropolymer platforms) reveals a fundamental commercialization gap in next-generation batteries. Organizations pursuing solid-state technology must decide whether to invest in high-risk novel materials or focus on incremental improvements to proven systems, with Asian competitors dominating both pathways.

9.3.2. Sustainable Polymers

The sustainable polymer landscape reveals sophisticated market segmentation, with electronics/semiconductors (47,723 patents) and textiles (40,973 patents) leading commercial adoption. Polyoxyalkylenes' prominence across applications reflects their processing versatility, while specialized biopolymers like PHBHHx (192% growth) and CMC derivatives (150-700% growth) target high-value niches. The integration of synthetic biology with polymer production, evidenced by 63:37 journal-to-patent ratios in monomer production, indicates ongoing challenges in scaling biological manufacturing despite strong research foundations.

Key Strategic Insight: Sustainable polymer has evolved from producing bio-based commodity equivalents to developing novel high-performance materials. Synthetic biology investments concentrate on monomers enabling high-performance applications - long-chain diacids and diamines for specialty polyamides, FDCA for barrier polyesters, succinate platforms for flexible biodegradable materials - rather than simply producing bio-based versions of commodity plastics. This explains why established petrochemical and chemical companies (Sinopec, Toray, Samsung) are heavily invested across both fermentation and polymer patents: sustainable polymers are evolving into performance materials requiring integrated capabilities across the value chain, not environmental alternatives competing solely on end-of-life benefits.

9.3.3. Flexible Electronics

The sector demonstrates clear regional specialization, with Asian companies controlling fundamental materials innovation while Western firms focus on high-value applications. Material selection shows application-driven differentiation: wearables exhibit 109% growth in fluoropolymers for energy harvesting; sensors show 74% growth in polyoxyalkylenes for strain detection; displays maintain conservative innovation around established polyimides and polyesters. The divergence between academic emphasis on bio-derived materials and industrial reliance on proven chemistries highlights persistent commercialization barriers for sustainable alternatives.

Key Strategic Insight: Success in flexible electronics depends less on novel polymer discovery than on systems engineering that integrates established materials into manufacturable device architectures. The patent landscape shows Asian leadership stems from optimizing proven platforms (polyimide, fluoropolymer) for specific processing requirements rather than breakthrough materials, suggesting competitive advantage lies in manufacturing capabilities and application-specific formulations rather than polymer chemistry innovation.

9.3.4. Membrane Technologies

Patent-dominated landscape (57% patents vs. 43% journals) indicates mature commercial development. Secondary battery separators show exceptional growth, reflecting energy storage demands. Geographic concentration is extreme, with Chinese institutions holding 29 of top 30 academic patent positions, led by Tiangong University's specialized membrane research infrastructure. Material trends favor established polymers (PVDF, PTFE) for reliability while emerging applications drive innovation in composite membranes (119% growth) and anion exchange membranes (433% growth in PP).

Key Strategic Insight: The membrane field presents a bifurcated opportunity landscape where established applications are led by entrenched competitors with optimized

manufacturing, while emerging applications (battery separators growing exceptionally, anion exchange membranes showing 400%+ growth) remain competitively fluid. The extreme Chinese institutional dominance in academic patents reflects deliberate national capability building, suggesting Western competitors should target emerging applications where material requirements still evolve rather than competing in mature membrane markets.

9.4 Emerging Frontiers and Future Trajectories

Analysis of NLP-derived trends and growth patterns identifies transformative technologies poised for mainstream adoption:

Next-Generation Polyesters: The diversification beyond PLA toward PBAT, PBS, PHBHHx, and PEF represents evolution from single biodegradable solutions to application-tailored portfolios balancing performance with end-of-life considerations.

Dynamic Polymer Networks: Vitrimers show explosive academic growth without corresponding patent activity, indicating fundamental breakthroughs awaiting commercial translation. Success requires addressing processing challenges and demonstrating economic viability for reprocessable thermosets.

Conductive Polymer Systems: The shift from studying intrinsic conductivity to integrating electrical properties with mechanical compliance, adhesion, and ionic mobility positions these materials for flexible electronics and energy storage applications.

Framework-Polymer Hybrids: MOF and COF integration with polymer matrices creates unprecedented property combinations. COFs' emergence as the primary growth driver (from minor component to dominant framework material by 2024) suggests breakthrough applications in catalysis and separation.

Actinic-Ray-Sensitive Polymers: Concentrated innovation from Fujifilm and Artience in sub-25nm lithography demonstrates how system-level integration of chemistry, processing, and characterization enables continued semiconductor scaling.

9.5 Strategic Implications and Recommendations

For Research Organizations: Success requires balancing fundamental discovery with application-oriented development. Institutions achieving high citation impact despite lower publication volumes demonstrate the value of focused, high-quality research over volume-based strategies. Collaboration with Asian manufacturing centers is essential for technology translation.

For Industry: The patent landscape reveals opportunities in underserved areas: chemical energy storage (1% of patents), sustainable electronics materials, and dynamic polymer networks. Companies must navigate the geographic concentration of innovation through strategic partnerships or regional R&D investments The patent analysis reveals strong activity from materials suppliers, though complete value chain dynamics require examining both materials and device patents together.

For Policymakers: The dramatic geographic shifts in innovation capacity have implications for technological sovereignty and supply chain security. Supporting domestic polymer innovation while facilitating international collaboration becomes critical. Regulatory frameworks must evolve with material innovations, particularly biodegradable polymers and bio-based production systems.

9.6 Challenges and Future Outlook

Despite remarkable progress, critical challenges persist:

The **translation gap** between academic research and commercial deployment remains significant, particularly for dynamic networks, conducting polymers, and bio-derived electronics materials. This indicates a need for new collaboration models to bridge fundamental science with industrial implementation.

Geographic imbalances create opportunities and vulnerabilities. While Asian dominance in volume metrics is clear, Western institutions maintain leadership in breakthrough innovations as measured by citation impact, suggesting complementary innovation models.

The **sustainability-performance-cost optimization** remains elusive for commodity applications. Despite technical advances, achieving simultaneous environmental, functional, and economic viability challenges widespread adoption of sustainable alternatives.

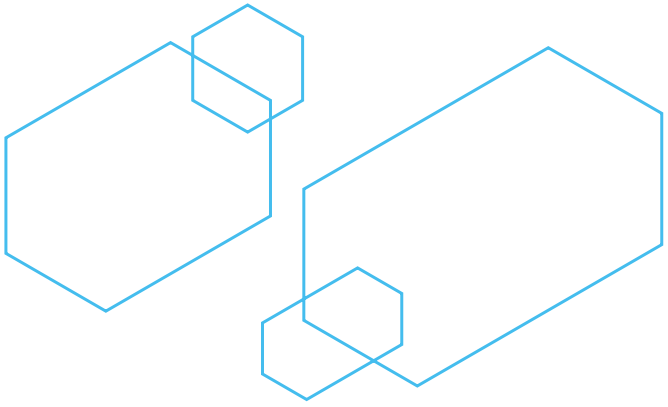
System complexity increasingly determines success. As polymers evolve from materials to integrated systems, success depends on coordinating multiple components, processes, and performance requirements, favoring organizations with comprehensive capabilities over specialized players.

9.7 Concluding Perspectives

The polymer science landscape emerging from this analysis represents a field at an inflection point. Traditional boundaries between disciplines, sustainability and performance, and materials and systems are dissolving and reforming in new configurations. The convergence of sustainability imperatives, digital manufacturing technologies, and global innovation networks is creating unprecedented opportunities for transformative advances.

The data suggests polymer science is evolving from a materials discipline to an enabling technology platform where success is measured by systemic impact rather than isolated properties. Organizations and regions that recognize this transformation, investing in multifunctional materials, sustainable production systems, and integrated manufacturing technologies, will shape the next decade of innovation.

As we look forward, the patterns identified in this analysis indicate that polymers will serve as the critical bridge between human needs and technological capabilities, enabling solutions to global challenges like climate change, resource scarcity, healthcare, and advanced manufacturing. The future belongs to those who can navigate this complexity while maintaining focus on creating materials that are high-performing, sustainable, processable, and accessible, truly embodying the promise of polymer science as a solutions science for the 21st century.



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Glossary and Abbreviations

Name	Abbreviations	CAS RN®
(±)-Poly(lactic acid)	(±)-PLA	26100-51-6
1,2-Benzenediol, 4-(2-aminoethyl)-, hydrochloride (1:1), homopolymer	PDA.HCl	1200398-97-5
1,3,5-Benzenetricarbonyl trichloride, polymer with 1,3-benzenediamine	m-PDA-TMC copolymer	83044-99-9
1,3,5-Benzenetricarbonyl trichloride, polymer with piperazine	TMC polymer with PIP	79122-60-4
1,3-Propanediol		504-63-2
1,4-Butanediol		110-63-4
1,5-Pentanediamine		462-94-2
2,2-Bis(3,4-dicarboxyphenyl)hexafluoropropane dianhydride-2,2-bis(trifluoromethyl)-4,4'-diaminobiphenyl copolymer	6FDA-TFDB copolymer	129197-26-8
2,5-Furandicarboxylic acid	FDCA	3238-40-2
2-piperidone		675-20-7
2-pyrrolidone		616-45-5
3-Hydroxyadipic acid		14292-29-6
4,4-Oxydianiline pyromellitic dianhydride copolymer	4,4'-ODA-PMDA copolymer	25038-81-7
5-hydroxymethylfurfural		67-47-0
Acrylamide-N,N'-methylenebisacrylamide copolymer	Acrylamide-MBAA copolymer	25034-58-6
Acrylic acid-2-ethylhexyl acrylate copolymer	AA–2EHA copolymer	25134-51-4
Acrylic acid-starch graft copolymer	Starch-g-PAA	9086-70-8
Acrylonitrile-butadiene copolymer	NBR	9003-18-3
Acrylonitrile-butadiene-styrene copolymer	ABS	9003-56-9
Adipic acid		124-04-9
Advanced engineering polymer materials	AEMs	
Agarose		9012-36-6
Alginic acid		9005-32-7
Alkali lignin		8068-05-1
Ammonium polyphosphate		68333-79-9
Aramid nanofibers	ANFs	
Atom Transfer Radical Polymerization	ATRP	
Bisphenol A	BPA	80-05-7
Bisphenol A diglycidyl ether homopolymer	poly(BADGE)	25085-99-8
Bisphenol A polysulfone		25135-51-7

Bisphenol F	BPF	1333-16-0
Butadiene-styrene copolymer	SBR	9003-55-8
Butadiene-styrene triblock copolymer	SBS	694491-73-1
Calcium alginate		9005-35-0
Carbon dioxide	CO2	124-38-9
Carboxylated nitrile rubber	XNBR	
Carrageenan		9000-07-1
CAS Registry Number	CAS RN	
Cellulose		9004-34-6
Cellulose acetate		9004-35-7
Cellulose carboxymethyl ether	CMC ether	9000-11-7
Cellulose, carboxymethyl ether, lithium salt	CMC-Li	55962-76-0
Cellulose-epichlorohydrin copolymer	Cellulose-ECH copolymer	37337-21-6
Chemically amplified resists	CAR	
China National Petroleum Corporation	CNPC	
Chitosan		9012-76-4
Chitosan-glutaraldehyde copolymer		75578-61-9
Chlorotrifluoroethylene-vinylidene fluoride copolymer	CTFE-VDF	9010-75-7
Conductive polymer composite	CPC	
Contemporary Amperex Technology Co., Limited	CATL	
Covalent adaptable networks	CANs	
Covalent organic framework	COF	
Dextrin		9004-53-9
Dialdehyde cellulose		9032-52-4
Dielectric constant	k	
Digital light processing	DLP	
Direct ink writing	DIW	
Dodecylphenol polyoxyethylene ether		9014-92-0
Dynamic polymer networks	DPNs	
Electrocardiogram	ECG	
Electroluminescent	EL	
Electromagnetic interference	EMI	
Electromyography	EMG	
Electronic skin	E-skin	

Epichlorohydrin		106-89-8
Ethylcellulose		9004-57-3
Ethylene propylene diene monomer	EPDM	
Ethylene-1-octene copolymer		26221-73-8
Ethylene-propylene copolymer	EPC	9010-79-1
Ethylene-tetrafluoroethylene copolymer	ETFE	25038-71-5
Ethylene-vinyl acetate copolymer	PEVA	24937-78-8
Extreme ultra-violet	EUV	
Ferrous oxide		1345-25-1
Fluorinated ethylene propylene	FEP	25067-11-2
Four-dimensional	4D	
Fructose		57-48-7
Furandicarboxylic acid		58465-65-9
Fused filament fabrication	FFF	
Glass transition temperature	Tg	
Glucose		50-99-7
Glycerol		56-81-5
Glycolide polymer		26202-08-4
Hexadecyltrimethylammonium bromide		57-09-0
Hexafluoropropylene-vinylidene fluoride copolymer	HFP-VDF	9011-17-0
High-density polyethylene	HDPE	
Hydrogen-bonded organic frameworks	HOFs	
Hydroxide ion		14280-30-9
Hydroxymethylcellulose		37353-59-6
Hydroxypropyl methyl cellulose	HPMC	9004-65-3
Indium tin oxide	ITO	50926-11-9
Infrared	IR	
Iodonium		43413-76-9
Ionic conductive elastomers	ICE	
Isotactic polypropylene	Isotactic PP	25085-53-4
Korea Research Institute of Chemical Technology	KRICT	
Lactic acid		50-21-5
Light-emitting diode	LED	
Lignin		9005-53-2

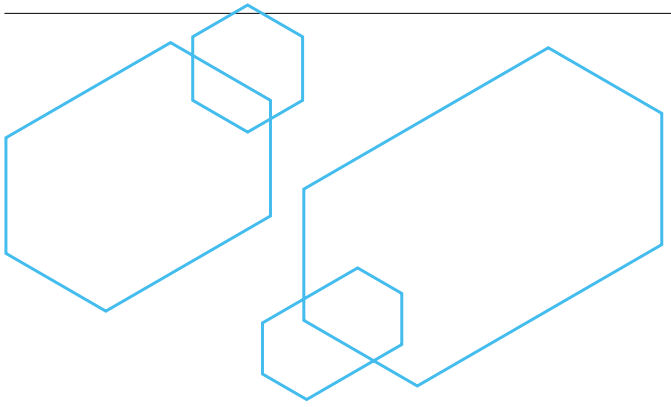
Lignosulfonic acid		8062-15-5
Linear low-density polyethylene	LLDPE	
Liquid crystal elastomer	LCE	
Lithium-ion	Li-ion	17341-24-1
Lithium ion batteries	LIBs	
Low-density polyethylene	LDPE	
Lysine		56-87-1
Maltodextrin		9050-36-6
Metal-organic framework	MOF	
Methylcellulose		9004-67-5
Microbial poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	Microbial PHBV	160555-53-3
Nafion 117		66796-30-3
Natural language processing	NLP	
Non-isocyanate polyurethane	NIPU	
Numercial aperture	NA	
O-carboxymethylchitosan		62711-98-2
Organic light emitting diodes	OLED	
Organic thin-film transistors	OTFT	
Oxirane, 2-methyl-, polymer with carbon dioxide	PPC	25511-85-7
Perfluoroalkoxy alkane	PFA	
Phase change material	PCM	
Photoacid generator	PAG	
Piezoelectric nanogenerators	PENG	
Poly 2-methoxyethyl acrylate	PMEA	28628-64-0
Poly N-isopropylacrylamide	PNIPAM	25189-55-3
Poly(2,6-dimethyl-1,4-phenylene ether)		24938-67-8
Poly(2,6-xylenol)		25134-01-4
Poly(3,4-ethylenedioxythiophene)	PEDOT	126213-51-2
Poly(3-hydroxybutyrate)	P3HB	26063-00-3
Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)	PHBHHx	147398-31-0
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)	PHBV	80181-31-3
Poly(3-hydroxybutyrate-co-4-hydroxybutyrate)	P(3HB-co-4HB)	117068-64-1
Poly(9,9-dioctylfluorene-alt-benzothiadiazole)	PFBT	210347-52-7
Poly(acrylic acid)		9003-01-4

Poly(butylene fumarate)	PBF	
Poly(butylene succinate)	PBS	26247-20-1
Poly(butylene succinate-co-terephthalate)	PBST	144123-61-5
Poly(butylene terephthalate)	PBT	24968-12-5
Poly(diallyldimethylammonium chloride)	PolyDADMAC	26062-79-3
Poly(dimethylsiloxane)	PDMS	31900-57-9
Poly(dopamine)	PDA	86389-83-5
Poly(ethoxylated trimethylolpropane triacrylate)		28961-43-5
Poly(ethylene naphthalenedicarboxylate)	PEN	9020-73-9
Poly(ethylene terephthalate)	PET	25038-59-9
Poly(glycolic acid)	PGA	26124-68-5
Poly(hydroxybutyrate)	PHB	52352-27-9
Poly(lactic acid)	PLA	26023-30-3
Poly(lactic-co-glycolic acid)	PLGA	34346-01-5
Poly(L-aspartic acid)		25608-40-6
Poly(L-glutamic acid)		25513-46-6
Poly(L-lactic acid), SRU	L-PLA	26161-42-2
Poly(methyl methacrylate)	PMMA	9011-14-7
Poly(m-phenyleneisophthalamide)	PMIA	24938-60-1
Poly(N-vinylcarbazole)	PVK	25067-59-8
Poly(oxy-1,2-ethanediyl), α-[[[3-(triethoxysilyl)propyl]amino]carbonyl]-ω-hydroxy-(9CI, ACI)	TPU	74695-91-3
Poly(oxy-1,4-phenyleneoxy-1,4-phenylenecarbonyl-1,4-phenylene)	PEEK-HT	31694-16-3
Poly(p-phenylenevinylene)	PPV	26009-24-5
Poly(propylene fumarate)	PPF	27083-66-5
Poly(styrenesulfonic acid)	PSS	50851-57-5
Poly(tetrahydrofuran)	PTHF	24979-97-3
Poly(trimethylene terephthalate)	PTT	26546-03-2
Poly(vinyl acetate)	PVAc	9003-20-7
Poly(vinyl alcohol)	PVA	9002-89-5
Poly(vinyl butyral)	PVB	915977-69-4
Poly(vinyl chloride)	PVC	9002-86-2
Poly(vinylidene fluoride)	PVDF	24937-79-9
Poly(vinylidene-trifluoroethylene)	P(VDF-TrFE)	28960-88-5

Poly(vinylpyrrolidone)	PVP	9003-39-8
Poly[[4,8-bis[5-(2-ethylhexyl)-2-thienyl]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl]-2,5-thiophenediyl[5,7-bis(2-ethylhexyl)-4,8-dioxo-4H,8H-benzo[1,2-c:4,5-c']dithiophene-1,3-diyl]-2,5-thiophenediyl]	PBDB-T	1415929-80-4
Poly[2,1,3-benzothiadiazole-4,7-diyl(9,9-dioctyl-9H-fluorene-2,7-diyl)	PFO-BT	
Poly[2,2'-(m-phenylene)-5,5'-bibenzimidazole]	m-PBI	25734-65-0
Poly[imino-1,5-pentanediylimino(1,10-dioxo-1,10-decanediyl)]	PA510	105063-19-2
Poly[imino-1,5-pentanediylimino(1,6-dioxo-1,6-hexanediyl)]	PA56	41724-56-5
Polyacrylamide	PAM	9003-05-8
Polyacrylonitrile	PAN	25014-41-9
Polyamdie 1010 /(poly[imino(1,10-dioxo-1,10-decanediyl)imino-1,10-decanediyl])	PA 1010	28774-87-0
Polyamdie 11/Nylon 11/ (undecanoic acid, 11-amino-, homopolymer)	PA 11	25587-80-8
Polyamide 1012/ Poly[imino-1,10-decanediylimino(1,12-dioxo-1,12-dodecanediyl)]	PA 1012	55426-60-3
Polyamide 12/Nylon 12/(poly[imino(1-oxo-1,12-dodecanediyl)])	PA 12	24937-16-4
Polyamide 4/Nylon 4/(poly[imino(1-oxo-1,4-butanediyl)])	PA 4	24938-56-5
Polyamide 6/Nylon 6 / (Poly[imino(1-oxo-1,6-hexanediyl)])	PA 6	25038-54-4
Polyamide 610/ Nylon 610	PA 610	9008-66-6
Polyamide 612/ (poly[imino-1,6-hexanediylimino(1,12-dioxo-1,12-dodecanediyl)])	PA 612	24936-74-1
Polyamide 66	PA 66	32131-17-2
Polyamide-imides	PAI	
Polyaniline	PANI	25233-30-1
Polybutadiene		9003-17-2
Polybutadiene rubber	BR	
Polybutylene adipate terephthalate	PBAT	130479-65-1
Polybutylene succinate adipate/Adipic acid-1,4-butanediol-succinic acid copolymer	PBSA	67423-06-7
Polycaprolactone	PCL	24980-41-4
Poly-D-Lactic Acid		106989-11-1
Polyelectrolyte multilayer	PEM	
Polyethersulfone	PESU	
Polyethylene furanoate/2,5-Furandicarboxylic acid, polymer with 1,2-ethanediol	PEF	27598-47-6
Polyethylene glycol	PEG	25322-68-3
Polyethylene glycol diacrylate	PEG diacrylate	26570-48-9
Polyethylene glycol dimethacrylate	PEG dimethacrylate	25852-47-5
Polyethylene glycol methyl ether acrylate	PEG methyl ether acrylate	32171-39-4
Polyethylene glycol methyl ether methacrylate	PEG methyl ether methacrylate	26915-72-0

Polyethylene Terephthalate Glycol	PETG	25038-91-9
Polyethylene/ Polyethene/ Ethene, homopolymer	PE	9002-88-4
Polyethylenimine	PEI	26913-06-4
Polyhydroxyalkanoate	PHA	
Polyhydroxyurethane	PHU	
Polyisoprene (1,3-butadiene, 2-methyl-, homopolymer)		9003-31-0
Poly-L-Lactic Acid		26811-96-1
Poly-L-lysine		38000-06-5
Polylysine		25104-18-1
Polypropylene glycol	PPG	25322-69-4
Polypropylene glycol diamine		9046-10-0
Polypropylene/ 1-Propene, homopolymer	PP	9003-07-0
Polypyrrole	PPy	30604-81-0
Polystyrene		9003-53-6
Polytetrafluoroethylene	PTFE	9002-84-0
Polytetramethylene glycol	PTMG	25190-06-1
Polythiophene	PT	25233-34-5
Potassium alginate		9005-36-1
p-Phenylenediamine-terephthalic acid copolymer, SRU	PPTA	24938-64-5
Pressure-sensitive adhesive	PSA	
Putrescine		110-60-1
Quaternary ammonium polymer	polyQAC	
Reversible Addition-Fragmentation chain Transfer	RAFT	
Ring-opening metathesis polymerization	ROMP	
Sebacic acid		111-20-6
Silica	SiO2	7631-86-9
Silicon		7440-21-3
Silver	Ag	7440-22-4
Sodium alginate		9005-38-3
Sodium carboxymethyl cellulose	CMC-Na	9004-32-4
Sodium carboxymethyl starch	CMS-Na	9063-38-1
Sodium polyacrylate		9003-04-7
Sodium-ion	Na-ion	17341-25-2
Starch		9005-25-8

Stereolithography	SLA	
Styrene-butadiene rubber, hydrogenated, block, triblock	HSBR, block, triblock	
Styrenic block copolymers	SBCs	
Succinic acid		110-15-6
Sulfonium		18155-21-0
Terephthalic acid		100-21-0
Thermal energy storage	TES	
Thermoplastic elastomers	TPEs	
Thermoplastic Polyamide Elastomers	TPAEs	
Thermoplastic Polyester Elastomers	TPEEs	
Thin film transistor	TFT	
Three-dimensional	3D	
Tiangong University	TU	
Triboelectric nanogenerators	TENG	
Trimethylsilyl-terminated poly(dimethylsiloxane)	TMS-PDMS	42557-10-8
Ultraviolet	UV	
United States	U.S.	
Valerate		10023-74-2
Volatile organic compound	VOC	
Xanthan gum		11138-66-2
Zeolitic imidazolate frameworks	ZIFs	
α-hydromuconic acid		4440-68-0
ε-Poly-L-lysine		28211-04-3



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Founded in December 2021, PetroChina (Shanghai) Advanced Materials Research Institute Co., Ltd. (SAMRI) is located in Lin-gang Special Area, Shanghai, China. SAMRI features a 72,000-square-meter innovation center in Shanghai equipped with the latest advanced scientific instrumentation complemented with demonstration plants in Nantong, Jiangsu Province, forming an integrated innovation ecosystem for development and up-scaling of technologies. SAMRI continues to expand its capabilities that will encompass a professional team of approximately 1,000 members. Industry leading experts and high-caliber scientists join force at SAMRI, among which 72% hold doctoral degrees, sharing the mission to build a world-class innovation hub having superior technological strength and a state-of-the-art management system.

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CASREP102881ENG

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