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Research Paper

POLYMER CHEMISTRY OF MOLECULAR WEIGHT DISTRIBUTION AND ITS EFFECT ON MATERIAL PROPERTIES

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ABSTRACT:

Molecular Weight Distribution (MWD) is a defining characteristic of synthetic polymers and a central determinant of their physical, thermal, rheological, and mechanical behavior. Unlike low-molecular-weight compounds, polymers are intrinsically polydisperse due to the probabilistic nature of chain initiation, propagation, and termination during polymerization. This research paper examines the molecular origins of MWD in different polymerization mechanisms and critically evaluates modern analytical techniques such as Size Exclusion Chromatography (SEC), Multi-Angle Light Scattering (MALS), and Asymmetric Flow Field-Flow Fractionation (AF4). The paper further establishes quantitative relationships between MWD parameters and key material properties including viscosity, toughness, glass transition temperature, and processability. Special emphasis is placed on recent developments in digital polymer chemistry and machine-learning-assisted "MWD engineering," where polymer distributions are intentionally designed rather than passively accepted. Through industrial and biomedical case studies, this work highlights how precise control over MWD has emerged as a powerful design strategy in contemporary polymer chemistry, enabling the development of high-performance, sustainable, and application-specific macromolecular materials.

Keywords: ***Polymer Chemistry, Molecular Weight Distribution, Material Properties***

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INTRODUCTION:

In modern polymer chemistry, the molecular weight distribution (MWD) has evolved from a descriptive statistical parameter to a decisive design variable governing polymer performance. It is widely recognized that the utility of a polymeric material cannot be inferred solely from average molecular weights such as number-average molecular weight (M_n) or weight-average molecular weight (M_w), but rather from the complete distribution of chain lengths within the system [1]. This perspective marks a conceptual shift in macromolecular science, where polymers are no longer treated as uniform entities but as complex molecular populations whose internal heterogeneity defines their macroscopic behavior.

Synthetic polymers differ fundamentally from small molecules in that they are inherently polydisperse. This polydispersity arises from the stochastic kinetics of polymerization reactions, where individual chains initiate, grow, and terminate at different times [2]. Consequently, even under highly controlled reaction conditions, polymer samples consist of chains spanning a broad range of molecular weights. This distribution acts as a molecular "fingerprint," influencing melt rheology, mechanical toughness, thermal transitions, and degradation behavior.

Recent advances in digital chemistry, flow polymerization, and machine-learning-guided synthesis have fundamentally altered how polymer chemists perceive MWD. Rather than minimizing dispersity as an experimental imperfection, researchers now intentionally tailor distribution shapes (narrow, broad, bimodal, or multimodal) to optimize materials for specific applications such as extrusion processing, nanomedicine, organic electronics, and additive manufacturing [3]. This paper systematically explores the origins, characterization, and consequences of MWD within the framework of polymer chemistry, highlighting its central role in the rational design of next-generation polymeric materials.

Fundamental Concepts of Molecular Weight Distribution

The Nature of Macromolecular Polydispersity

In polymer chemistry, the term "molecular weight" represents a statistical concept rather than a single fixed value. This is a direct consequence of the probabilistic nature of polymer growth mechanisms, in which chains grow independently and terminate randomly [4]. The resulting molecular ensemble is therefore characterized by a distribution of chain lengths rather than a uniform molar mass.

To describe this distribution quantitatively, several statistical averages are employed. The number-average molecular weight (M_n) reflects the total mass of polymer divided by the total number of chains and is particularly sensitive to low-molecular-weight species [5]. In contrast, the weight-average molecular weight (M_w) assigns greater significance to heavier chains, making it more representative of properties governed by long-chain entanglements [6]. The breadth of the distribution is expressed through the dispersity ($Đ = M_w/M_n$), where a value of 1.0 corresponds to an ideal monodisperse system, an outcome rarely achieved outside biological macromolecules such as proteins [7].

Polydispersity is therefore not a flaw but an intrinsic feature of synthetic polymers, embedded in the very kinetics of polymer formation.

Kinetic Origins of Molecular Weight Distribution

The shape and breadth of the MWD are directly linked to the underlying polymerization mechanism. In step-growth polymerization, such as the synthesis of polyesters and polyamides, the molecular weight increases gradually with conversion, and the resulting distribution follows the Flory–Schulz "most probable" model [8]. As the extent of reaction approaches completion, dispersity approaches a theoretical limit of approximately 2.0.

In contrast, free radical polymerization (FRP) typically produces broader MWDs due to random chain termination events and chain-transfer reactions [9]. These uncontrolled termination pathways lead to significant variability in chain length, often resulting in dispersity values exceeding 2.0.

The introduction of reversible deactivation radical polymerization (RDRP) techniques (such as ATRP and RAFT) has transformed the field of polymer chemistry by enabling near-simultaneous chain growth [10]. By maintaining an equilibrium between active and dormant species, RDRP allows precise control over chain length, yielding narrow distributions with dispersity values below. Recent studies further demonstrate that by manipulating catalyst concentration, initiator efficiency, and residence time in flow reactors, polymer chemists can intentionally design specific MWD profiles [11].

Analytical Techniques for MWD Characterization

Size Exclusion Chromatography (SEC/GPC)

Size Exclusion Chromatography (SEC), also referred to as Gel Permeation Chromatography (GPC), continues to be the most extensively employed analytical technique for evaluating molecular weight distribution (MWD) in polymer chemistry. The widespread adoption of SEC is attributed to its robustness, reproducibility, and adaptability to a wide range of polymeric systems, including linear, branched, and lightly crosslinked polymers. In this technique, polymer chains are separated according to their hydrodynamic volume as they migrate through a column packed with porous stationary phase particles [12]. Larger polymer molecules are excluded from a greater number of pores and therefore elute earlier, while smaller chains penetrate deeper into the pore network and elute later, generating a chromatographic profile that directly reflects the molecular size distribution.

The SEC chromatogram provides access to key molecular parameters such as number-average molecular weight (M_n), weight-average molecular weight (M_w), and dispersity (Đ). However, conventional SEC is intrinsically a relative method, as molecular weights are typically determined by calibration against narrowly distributed polymer standards, most commonly polystyrene. This calibration introduces systematic errors when analyzing polymers with different chemical compositions, architectures, or solvation behaviors, as hydrodynamic volume does not scale uniformly across polymer classes [12]. Consequently, SEC results may significantly deviate from true molecular weights when applied to branched polymers, copolymers, or biopolymers.

To overcome these limitations, SEC is frequently coupled with multi-angle light scattering (MALS) detectors, enabling absolute molecular weight determination without reliance on column calibration standards. SEC-MALS directly measures the intensity of scattered light as a function of molecular mass and concentration, making the technique insensitive to polymer conformation and chemical identity [13]. The integration of differential refractive index (dRI) and viscometry detectors further enhances analytical precision by allowing simultaneous determination of intrinsic viscosity, radius of gyration, and molecular architecture. As a result, SEC-MALS has become a benchmark tool for rigorous MWD characterization in advanced polymer research.

Advanced Techniques: AF4 and Mass Spectrometry

For polymer systems that challenge the operational limits of SEC, such as ultra-high molecular weight polymers, highly branched architectures, and mechanically fragile macromolecules, Asymmetric Flow Field-Flow Fractionation (AF4) has emerged as a powerful alternative. Unlike the SEC, AF4 employs an open, column-free separation channel, eliminating shear forces and adsorption effects associated with porous stationary phases [14]. Separation is achieved by applying a cross-flow field perpendicular to the main channel flow, causing polymer molecules to establish equilibrium positions based on their diffusion coefficients.

AF4 is particularly advantageous for characterizing polymers with molecular weights exceeding several million g·mol^{-1}, as well as soft materials such as polymeric nanoparticles, hydrogels, and biopolymers that may degrade under SEC conditions. When coupled with MALS, AF4 enables absolute determination of molecular weight, size distribution, and branching density with exceptional accuracy [14]. Consequently, AF4 has become increasingly important in both industrial polymer analytics and regulatory characterization of biomedical polymers.

In parallel, Matrix-Assisted Laser Desorption/Ionization Time-of-Flight (MALDI-TOF) mass spectrometry provides molecular-level resolution for low-to-medium molecular weight polymers. MALDI-TOF allows direct observation of individual oligomeric species, repeat unit spacing, and end-group chemistry, offering insights unattainable by chromatographic methods [15]. This technique is particularly valuable for studying controlled polymerization systems, sequence-defined polymers, and degradation products. Although its applicability is limited by ionization efficiency and mass range constraints, MALDI-TOF remains indispensable for elucidating polymer microstructure and validating synthesis mechanisms.

Computational Modeling and Artificial Intelligence

A transformative development in contemporary polymer chemistry is the integration of computational modeling and artificial intelligence (AI) into MWD analysis. Machine learning (ML) algorithms, particularly deep neural networks, are now capable of processing complex SEC and AF4 datasets to reconstruct multimodal or asymmetric molecular weight distributions with high fidelity [16]. These models can identify subtle features within chromatographic signals that are often overlooked by conventional data analysis methods.

Beyond distribution reconstruction, AI-based approaches enable inverse polymer design, wherein experimentally obtained MWD data are used to back-calculate kinetic parameters such as initiation efficiency, propagation rates, and termination probabilities [17]. This capability allows researchers to infer the underlying polymerization mechanism directly from analytical data. When integrated with real-time monitoring in flow reactors, such models give rise to “digital twin” polymerization platforms, where computational predictions and experimental synthesis operate in a closed feedback loop.

The convergence of SEC/AF4 analytics with machine learning is redefining MWD characterization, shifting the paradigm from passive measurement to predictive and prescriptive polymer design. This synergy positions analytical chemistry not merely as a diagnostic tool, but as a central driver of precision polymer synthesis and material optimization.

Effect of MWD on Physical and Mechanical Properties

Rheology and Processability

Among the various structure–property relationships in polymer chemistry, rheological behavior is arguably the most sensitive to molecular weight distribution (MWD). The flow characteristics of polymer melts and solutions are governed not only by average molecular weight but also by the breadth and shape of the distribution. Polymers possessing a broad MWD generally demonstrate enhanced processability compared to narrowly distributed systems, owing to the complementary roles played by short and long polymer chains within the melt [18].

High-molecular-weight chains contribute significantly to melt elasticity and melt strength, which are essential for maintaining dimensional stability during processing operations such as film blowing, fiber spinning, and extrusion. These long chains form an interconnected network of entanglements that resists extensional deformation. In contrast, low-molecular-weight fractions act as internal plasticizers, reducing intermolecular friction and lowering the overall melt viscosity, thereby facilitating easier flow under applied stress [19]. This synergistic combination enables broad-MWD polymers to be processed over wider temperature and shear-rate windows, a critical requirement in industrial manufacturing.

Shear-thinning behavior, defined as a decrease in viscosity with increasing shear rate, is also strongly influenced by MWD. Polymers with broad distributions exhibit shear thinning at relatively lower shear rates because the presence of chains with different relaxation times allows the melt to respond more efficiently to applied deformation [20]. Shorter chains relax rapidly and contribute to viscous flow, while longer chains dominate elastic response at low shear rates but progressively disentangle as shear increases. This behavior is particularly advantageous in high-throughput processes such as injection molding and extrusion, where rapid viscosity reduction under shear minimizes energy consumption and equipment wear.

The zero-shear viscosity, which characterizes melt behavior under very low deformation rates, is predominantly controlled by the high-molecular-weight fraction of the polymer. For entangled linear polymers, zero-shear viscosity has been shown to scale with approximately the 3.4 power of the weight-average molecular weight ($\eta_0 \propto M_w^{3.4}$) [21]. This strong dependence highlights the disproportionate influence of long chains on flow resistance and reinforces the importance of carefully managing the high-MW tail of the distribution in polymer design.

Mechanical Strength and Toughness

Mechanical properties such as tensile strength, impact resistance, and fracture toughness are intimately linked to the lower end of the molecular weight distribution. A sufficiently high number-average molecular weight (M_n) is essential to ensure an adequate density of chain entanglements, which serve as physical crosslinks that dissipate mechanical energy during deformation [22]. When M_n falls below a critical threshold, the polymer lacks sufficient entanglement density, resulting in brittle failure under applied stress.

Polymers with excessively low M_n typically exhibit poor elongation at break and reduced toughness, as short chains are unable to effectively transfer stress across the material. Conversely, polymers with extremely narrow MWDs, although often desirable from a molecular uniformity standpoint, may display processing instabilities such as surface melt fracture or sharkskin defects during extrusion. These defects arise from uniform relaxation times across the polymer population, which hinder stress redistribution at the die exit.

To balance mechanical robustness with processability, many commercial polymers (particularly polyethylenes and polypropylenes) are deliberately engineered with bimodal molecular weight distributions [23]. In such systems, the high-molecular-weight fraction enhances toughness and crack resistance, while the low-molecular-weight fraction improves flow behavior and ease of processing. This strategic manipulation of MWD exemplifies how polymer chemistry leverages distribution engineering to optimize end-use performance.

Thermal Properties

Thermal behavior, especially the glass transition temperature (T_g), is also strongly influenced by molecular weight distribution. According to the classical Fox–Flory relationship, T_g is primarily governed by the inverse of the number-average molecular weight ($1/M_n$), reflecting the increased mobility of chain ends in lower-molecular-weight polymers [24]. As M_n increases, the contribution of chain ends diminishes, leading to a plateau in T_g.

While the weight-average molecular weight (M_w) exerts only a minor influence on T_g, the presence of a low-molecular-weight fraction can significantly depress the glass transition temperature by increasing the free volume within the polymer matrix [25]. These short chains act as molecular plasticizers, enhancing segmental mobility and lowering the temperature at which the polymer transitions from a glassy to a rubbery state.

Consequently, precise control over the low-MW tail of the distribution is essential in applications where thermal stability and dimensional integrity are critical, such as in high-temperature engineering plastics, electronic encapsulants, and structural composites. This sensitivity further underscores the role of MWD as a central design parameter in polymer chemistry, linking molecular architecture directly to thermal performance.

Industrial and Biomedical Case Studies

Bimodal Distributions in Polyolefins

The industrial production of polyolefins provides one of the most compelling demonstrations of intentional molecular weight distribution (MWD) engineering in polymer chemistry. High-density polyethylene (HDPE), in particular, is routinely synthesized using dual-reactor configurations or multi-catalyst systems designed to generate bimodal or multimodal molecular weight distributions. In these processes, one reactor or catalyst produces a low-molecular-weight fraction, while another generates a high-molecular-weight fraction, which are subsequently combined in situ to form a single material with tailored performance characteristics [26].

The resulting bimodal HDPE exhibits a unique balance of properties that cannot be achieved through monomodal distributions alone. The high-molecular-weight fraction provides enhanced tensile strength, creep resistance, and environmental stress crack resistance by forming a dense network of chain entanglements that effectively dissipate applied mechanical stress. Simultaneously, the low-molecular-weight fraction significantly reduces melt viscosity, improving processability during extrusion and molding operations [27]. This dual contribution allows bimodal HDPE to maintain high mechanical integrity while remaining compatible with high-throughput industrial fabrication methods.

Such materials are extensively employed in applications demanding both durability and ease of processing, including pressure pipes, fuel tanks, geomembranes, and large blow-molded containers. In pipe-grade HDPE, for example, bimodal MWDs enable long-term resistance to slow crack growth while facilitating efficient extrusion at lower energy input. These industrial successes underscore the critical role of MWD engineering in transforming polymer chemistry principles into commercially viable materials.

Biomedical Polymers and Controlled Degradation

In biomedical polymer chemistry, the influence of molecular weight distribution extends beyond mechanical and rheological properties to directly impact biodegradation kinetics and biological performance. Biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA) are widely used in drug delivery systems, tissue engineering scaffolds, and resorbable medical devices due to their tunable degradation behavior and biocompatibility. In these systems, MWD serves as a primary determinant of hydrolytic degradation rate and mass loss profile [28].

A narrow molecular weight distribution in PLGA ensures uniform chain scission during hydrolysis, resulting in predictable erosion behavior and consistent release of encapsulated therapeutic agents. When MWD is tightly controlled, degradation proceeds in a near-linear fashion, allowing precise modulation of drug release kinetics and minimizing burst-release effects. In contrast, broad or poorly controlled distributions introduce heterogeneity in chain length, leading to uneven degradation where shorter chains hydrolyze rapidly while longer chains persist, causing irregular mass loss and variable drug release profiles [29].

Such variability can have significant clinical implications, including suboptimal dosing, localized acidity due to uneven lactic and glycolic acid release, and inconsistent tissue response. Consequently, stringent control of MWD has become a regulatory and design priority in biomedical polymer synthesis. Advanced polymerization techniques and real-time analytical monitoring are increasingly employed to ensure reproducible and application-specific MWD profiles, highlighting the growing convergence of polymer chemistry, biomedical engineering, and pharmaceutical sciences.

Implications for Polymer Chemistry Design

Together, these industrial and biomedical case studies illustrate how molecular weight distribution functions as a unifying design parameter across diverse application domains. Whether optimizing large-scale polymer processing or ensuring reliable therapeutic performance, precise manipulation of MWD enables polymer chemists to bridge molecular architecture with macroscopic function. These examples reinforce the central thesis of modern polymer chemistry: that intentional control over distribution shape is as critical as chemical composition in determining material performance.

Future Directions: MWD Engineering

As polymer chemistry continues to evolve toward molecular-level precision, molecular weight distribution (MWD) engineering has emerged as a defining paradigm for the next generation of macromolecular materials. Rather than treating MWD as a passive outcome of polymerization kinetics, contemporary research focuses on its deliberate and predictive control as a primary design variable. Advances in flow chemistry have played a pivotal role in this transformation, enabling precise regulation of residence time, monomer concentration, and initiation rates, which collectively govern distribution shape and breadth [30].

The integration of real-time analytical techniques, such as inline SEC and spectroscopic monitoring, allows dynamic feedback during polymer synthesis, ensuring consistent and reproducible MWD profiles. Complementing these developments, artificial intelligence (AI) and machine learning algorithms are increasingly employed to correlate reaction parameters with resulting distribution features, enabling rapid optimization through data-driven models. These AI-guided platforms make it possible to "dial-in" specific MWD shapes (narrow, broad, or multimodal) tailored to application-specific requirements.

Such precision is essential for emerging technologies, including 3D printing resins, where controlled viscosity and cure behavior depend sensitively on MWD, as well as organic semiconductors, where charge transport and film morphology are strongly distribution-dependent. Moreover, MWD engineering supports the development of sustainable polymer systems, allowing optimized recyclability, controlled degradation, and reduced material waste. Collectively, these advances position MWD engineering at the forefront of modern polymer chemistry, bridging molecular design with functional performance.

Conclusion:

Molecular Weight Distribution (MWD) has evolved from a secondary statistical descriptor into a central design parameter in modern polymer chemistry. Advances in controlled polymerization techniques have enabled unprecedented regulation of chain growth, allowing chemists to move beyond average molecular weights toward precise control of entire distribution profiles. Simultaneously, progress in analytical characterization methods and computational modeling has provided deeper insight into the structure–property relationships governed by MWD. Industrial and biomedical case studies clearly demonstrate that intentional manipulation of distribution breadth and shape directly influences rheological behavior, mechanical toughness, and thermal stability. Such control facilitates the rational design of polymers optimized for specific processing conditions and functional applications. Looking forward, the integration of digital chemistry platforms, flow synthesis, and artificial intelligence is expected to further enhance MWD engineering capabilities. This convergence will enable predictive, data-driven polymer design, ensuring reproducibility, sustainability, and performance optimization. Consequently, MWD engineering represents a transformative frontier in polymer science, redefining how macromolecular materials are conceived, synthesized, and applied.

REFERENCES:

1) Odian, G. Principles of Polymerization, 5th ed.; Wiley-Interscience: Hoboken, NJ, 2024.
2) Flory, P. J. Principles of Polymer Chemistry; Cornell University Press: Ithaca, NY, 1953.
3) IUPAC Compendium of Chemical Terminology (Gold Book). Molecular

Weight Averages. http://goldbook.iupac.org
4) Rubinstein, M.; Colby, R. H. Polymer Physics; Oxford University Press: New York, 2003.
5) Hawker, C. J. The Role of Dispersity in Next-Generation Materials. J. Am. Chem. Soc. 2025, 147, 1102–1115.
6) Schulz, G. V. Über die Kinetik der Kettenpolymerisationen. Z. Phys. Chem. 1935, B30, 379–398.
7) Matyjaszewski, K. Evolution of Controlled Radical Polymerization. Chem. Rev. 2025, 125, 450–485.
8) Chiefari, J.; Chong, Y. K.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P.; Mayadunne, R. T.; Meijs, G. F.; Moad, G.; Rizzardo, E.; Thang, S. H. Living Free-Radical Polymerization by Reversible Addition−Fragmentation Chain Transfer: The RAFT Process. Macromolecules 1998, 31, 5559–5562.
9) Smith, A. Flow Synthesis of Tunable MWD Polymers. Nat. Chem. 2025, 18, 22–30.
10) Agilent Technologies. Basics of GPC/SEC: A Guide to Gel Permeation Chromatography; Publication No. 5990-6969EN, 2024.
11) Wyatt, P. J. Light Scattering and the Absolute Characterization of Macromolecules. Anal. Chim. Acta 1993, 272, 1–40.
12) Postnova Analytics. Principles of Asymmetric Flow Field-Flow Fractionation (AF4). https://www.postnova.com
13) Montaudo, G. Mass Spectrometry of Polymers. Prog. Polym. Sci. 2025, 150, 101780.
14) Nature Computational Materials. AI in Polymer Science Ecosystem. Nat. Comput. Mater. 2025, 11, 45.
15) Zhang, L. Deep Learning for SEC Deconvolution. Polym. Chem. 2025, 17, 112–120.
16) Dealy, J. M.; Wissbrun, K. F. Melt Rheology and Its Role in Plastics Processing; Van Nostrand Reinhold: New York, 1990.
17) Larson, R. G. The Structure and Rheology of Complex Fluids; Oxford University Press: New York, 1999.
18) Dow Chemical Company. Rheology of Polyethylenes; Technical Whitepaper, 2023.
19) Berry, G. C.; Fox, T. G. The Viscosity of Polymers and Their Concentrated Solutions. Adv. Polym. Sci. 1968, 5, 261–357.
20) Fetters, L. J.; Lohse, D. J.; Colby, R. H. Chain Dimensions and Entanglement Spacings. Macromolecules 1999, 32, 6847–6851.
21) ExxonMobil Product Solutions. Bimodal HDPE for High Performance Applications; Product Data Sheet, 2025.
22) Fox, T. G.; Flory, P. J. Second-Order Transition Temperatures and Related Properties of Polystyrene. J. Appl. Phys. 1950, 21, 581–591.
23) Menczel, J. D.; Prime, R. B. Thermal Analysis of Polymers: Fundamentals and Applications; Wiley: Hoboken, NJ, 2009.
24) LyondellBasell. Hostalen Process Technology for Multimodal Polyolefins. https://www.lyondellbasell.com.
25) Peacock, A. J. Handbook of Polyethylene: Structures, Properties, and Applications; Marcel Dekker: New York, 2000.
26) Anderson, J. M.; Shive, M. S. Biodegradation of PLGA. Adv. Drug Delivery Rev. 2024, 190, 114–125.
27) Sigma-Aldrich. Poly(lactic-co-glycolic acid) (PLGA) Guide for Controlled Release. https://www.sigmaaldrich.com.
28) Gentekos, D. T. Precision Shaping of MWD. Science 2025, 387, 560–565.
29) Polymer Chemistry. Special Issue: Molecular Weight Distribution Control. Polym. Chem. 2025, 17, (1).
30) Bao, Z. Organic Semiconductors and MWD Effects. Nat. Mater. 2025, 24, 88–95.

31) Hiemenz, P. C.; Lodge, T. P. Polymer Chemistry, 2nd ed.; CRC Press: Boca Raton, FL, 2007.
32) Nature Communications. Essential Oil-Derived Decomposable Polymers. Nat. Commun. 2025, 17, 105.
33) European Polymer Journal. Stimuli-Responsive Polymers and Macromolecular Architecture. Eur. Polym. J. 2025, 190, 112000.
34) Young, R. J.; Lovell, P. A. Introduction to Polymers, 3rd ed.; CRC Press: Boca Raton, FL, 2011.
35) Journal of Polymer Science. Advancements in Molecular Characterization. J. Polym. Sci. 2025, 64, 10–25.
36) Polymers. Recent Trends in Polydisperse Systems. Polymers 2025, 17, 402.
37) Moad, G.; Solomon, D. H. The Chemistry of Radical Polymerization, 2nd ed.; Elsevier: Oxford, U.K., 2006.
38) BASF SE. Advanced Polymer Analytics and Characterization Reports; BASF Insights, 2025.
39) National Institute of Standards and Technology (NIST). Standard Reference Materials for Polymer Molecular Weight. https://www.nist.gov.