



Research Article

Polymer Associated BPA - Mechanistic Inside into Matrix Binding, Migration Potential and Regulatory Consideration

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Bisphenol A (BPA) remains an indispensable yet heavily scrutinized monomer in modern polymer chemistry. This review provides a mechanistic overview of polymer-associated BPA, elucidating its structural incorporation, matrix binding affinity, and migration kinetics from polymer materials. We contrast the rigid covalent cross-linking of BPA within polycarbonate and epoxy resin architectures against its dynamic, non-covalent interactions when serving as an additive or processing byproduct. The migration potential of residual or hydrolysed BPA monomers is governed heavily by thermodynamic partitioning and Fickian diffusion processes, which are dramatically accelerated by external stressors like thermal degradation, pH imbalances, and solvent swelling. Given its well-documented role as an endocrine-disrupting chemical, we synthesize current high-performance analytical techniques used for trace quantification. Finally, we review evolving global regulatory landscape policies, such as the transition toward "BPA-Non-Intent" (BPA-NI) matrices, and discuss the socioeconomic challenges and technological bottlenecks impeding the deployment of safe, bio-based aromatic alternatives.

Keywords: Bisphenol A; Matrix Binding; Diffusion Kinetics; Polycarbonate; Regulatory Frameworks; BPA-Non-Intent (BPA-NI).

INTRODUCTION

Graphical Abstract

This flowchart illustrates the degradation and leaching pathway of Bisphenol A (BPA) from consumer materials into surrounding environments. It begins in the polymer matrix, such as polycarbonate plastics or epoxy resins, where chemical bonds within the covalent backbone break down via hydrolysis and aging to release free BPA monomers. These monomers then travel through the material via Fickian

diffusion, a transport process heavily accelerated by external environmental stimuli like high temperatures, variable pH levels, or contact with lipids. Consequently, the free BPA migrates into target matrices, which include food simulants, natural ecosystems, or human physiological fluids. Ultimately, the diagram shows that strict regulatory interventions, such as the EU 2024/3190 directive and BPA-NI (BPA-Non-Intentional) standards, are applied at this final stage to restrict exposure and mitigate the risks associated with this chemical contamination

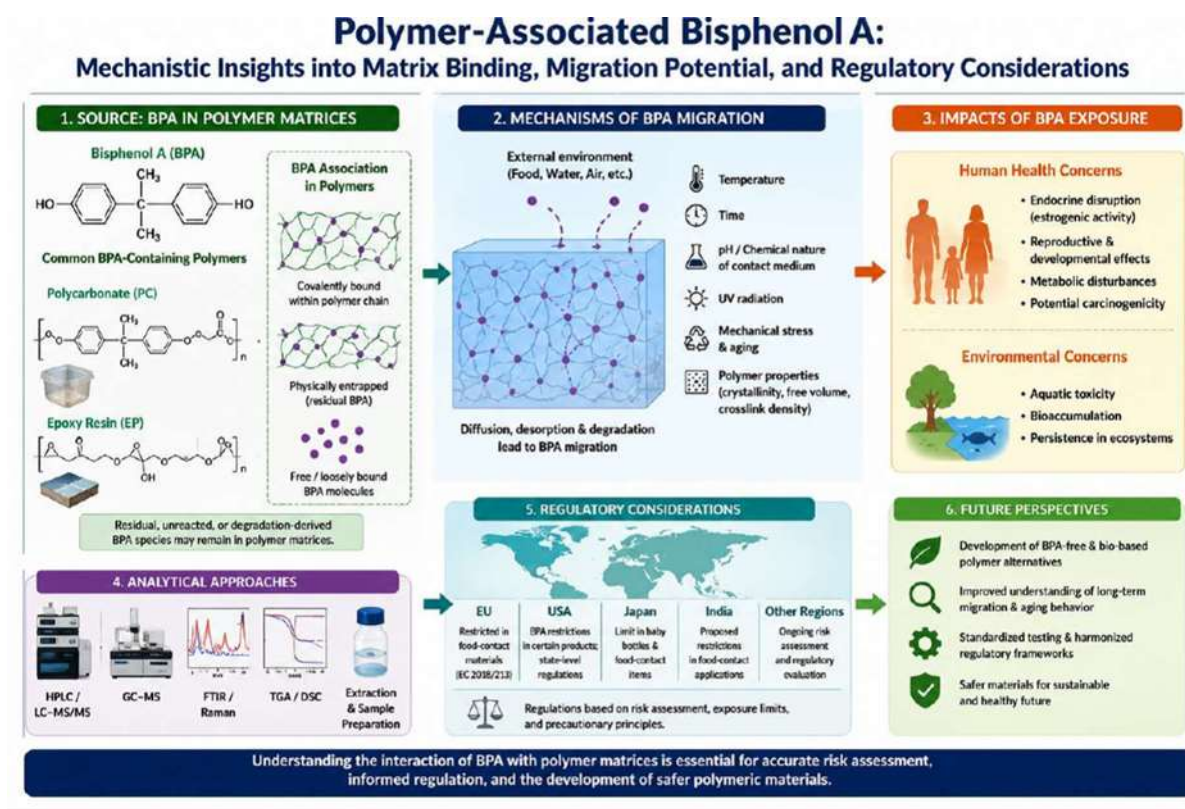


Figure: 1 Graphical Abstract

Novelty

This article uniquely bridges structural polymer physics with toxicology by presenting a unified mechanistic map detailing how atomic-level non-covalent interactions (e.g., π - π stacking) evolve over time into macroscopic environmental leaching phenomena, analyzed under the most recent 2024–2026 global chemical safety updates.

Research Highlights

1. Contrasts structural ester/ether covalent networks with free additives in polymer matrices.
2. Maps thermodynamic partitioning and Fickian diffusion pathways driving BPA migration.
3. Assesses advancements in modern legal frameworks, specifically the EU 2024/3190 "BPA-Non-Intent" (BPA-NI) mandate

1. Introduction

Bisphenol A (BPA) [2-(4-hydroxyphenyl) propan-2-yl] is one of the highest-volume synthetic compounds manufactured globally, acting as a foundational

building block for contemporary materials science. Originally synthesized in the late 19th century, its industrial application skyrocketed in the mid-20th century with the commercial explosion of clear, shatter-resistant polycarbonates and highly durable protective industrial coatings (Manzoor et al., 2022).

The ubiquity of BPA stems from its rigid symmetrical aromatic structure, which imparts exceptional mechanical toughness, optical clarity, and thermal stability to plastic matrices. However, because it behaves structurally like an estrogen analogue, its tendency to leach out of products has elevated it to a high-priority environmental contaminant and a classic endocrine-disrupting chemical (EDC) (Alenazi et al., 2016). Over time, structural polymer degradation and incomplete industrial polymerization leave unbound monomers highly susceptible to mobilization. Understanding the exact mechanical pathways governing matrix binding and transport kinetics remains a vital prerequisite for building safer chemical alternatives.

2. Occurrence of BPA in Polymer Matrices

2.1. Polycarbonate Polymer

Polycarbonate (PC) is synthesized via the interfacial polycondensation of BPA with phosgene or through transesterification with diphenyl carbonate. In these systems, BPA forms the core backbone via repeating ester linkages. While the bulk of the monomer is structurally locked away, unreacted residual traces inevitably remain trapped within the matrix space. Furthermore, exposure to high temperatures or alkaline cleaning agents induces back-bite hydrolysis of these ester chains, systematically regenerating free BPA monomers (Cimmino et al., 2020).

2.2. Epoxy-Based Material

Epoxy resins rely heavily on the reaction between BPA and epichlorohydrin to create BPA diglycidyl ether (BADGE). These cross-linked thermosetting polymers serve extensively as interior protective coatings for metal food and beverage cans (Muzeza et al., 2023). Because cross-linking density can vary significantly across production runs, unreacted phenolic groups can become trapped within the cross-linked network, serving as a long-term reservoir for potential chemical leaching.

2.3. Polymer Additives and Processing Environment

Beyond acting as a primary structural monomer, BPA is often utilized as a processing antioxidant or a polymerization inhibitor in polyvinyl chloride (PVC) formulations and other elastomeric blends (Manzoor et al., 2022). In these matrices, BPA is merely suspended as an additive without any protective covalent bonds. Furthermore, during high-shear melt processing, thermal degradation can generate localized chain scission, elevating free BPA levels before the product even hits the market.

3. Molecular Interaction between BPA and Polymer Networks

Within a polymer matrix, unbound BPA interacts with neighboring chains via a suite of weak intermolecular forces. The dual aromatic rings of the molecule engage in prominent π - π stacking arrangements with the phenyl groups of surrounding polymers. Concurrently, its terminal hydroxyl groups form transient hydrogen bonds with carbonyl or ether sites along the polymer backbone. While these non-covalent interactions temporarily hold the free monomer in place, they possess low activation energy thresholds. When the polymer shifts past its glass transition temperature (T_g), these weak networks rapidly detach, dramatically expanding the free volume available for molecular transport.

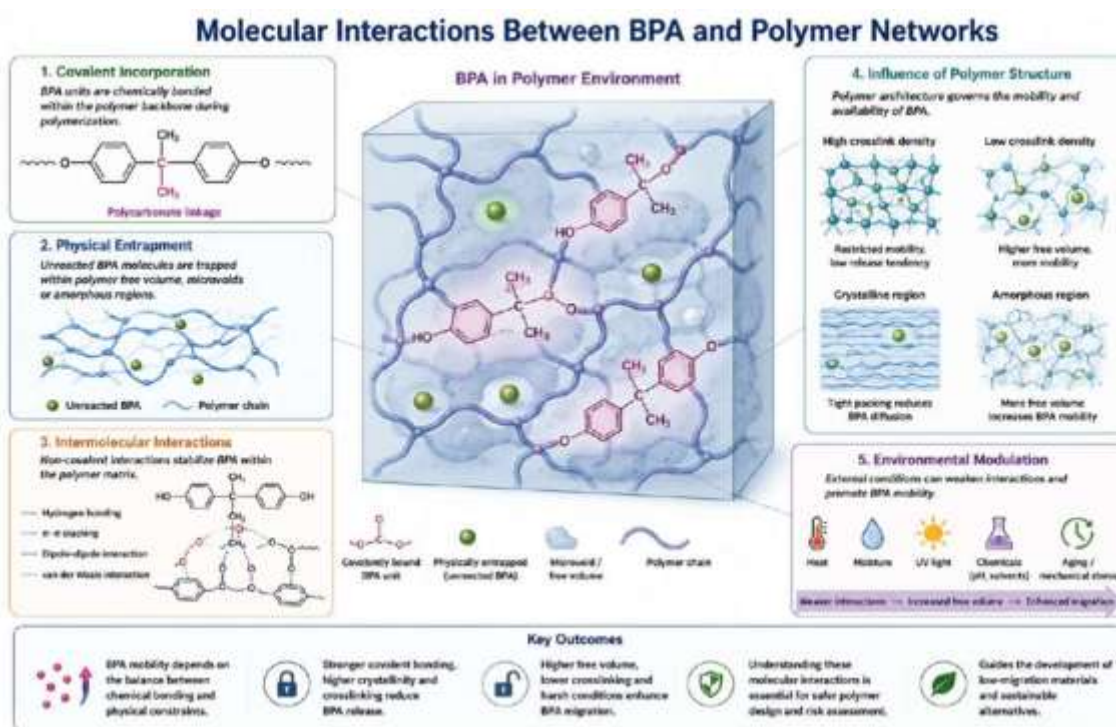


Figure: 2 Molecular Interaction between BPA and Polymer Networks

4. Mechanisms of BPA Migration from Polymer Matrices

The release of BPA follows a multi-stage transport pathway driven primarily by Fickian diffusion:

$$dC/dt = D * (d^2C/dx^2)$$

Here, the diffusion coefficient (D) increases exponentially when external media or lipids plasticize the polymer network. The physical types of release can be classified through distinct mechanical channels (Gupta et al., 2024; Muzeza et al., 2023):

- **Contact Migration:** The direct transfer of chemicals via physical contact with an external fluid or food matrix, dictated by concentration gradients.
- **Penetration Migration:** Monomers travel from non-contact outer areas through the polymer matrix to reach the inner contact layer.
- **Gas-Phase and Condensation Migration:** Driven by localized thermal shifts (such as boiling or microwave heating), volatile or semi-volatile compounds sublime into adjacent air spaces or condense onto nearby contact surfaces.

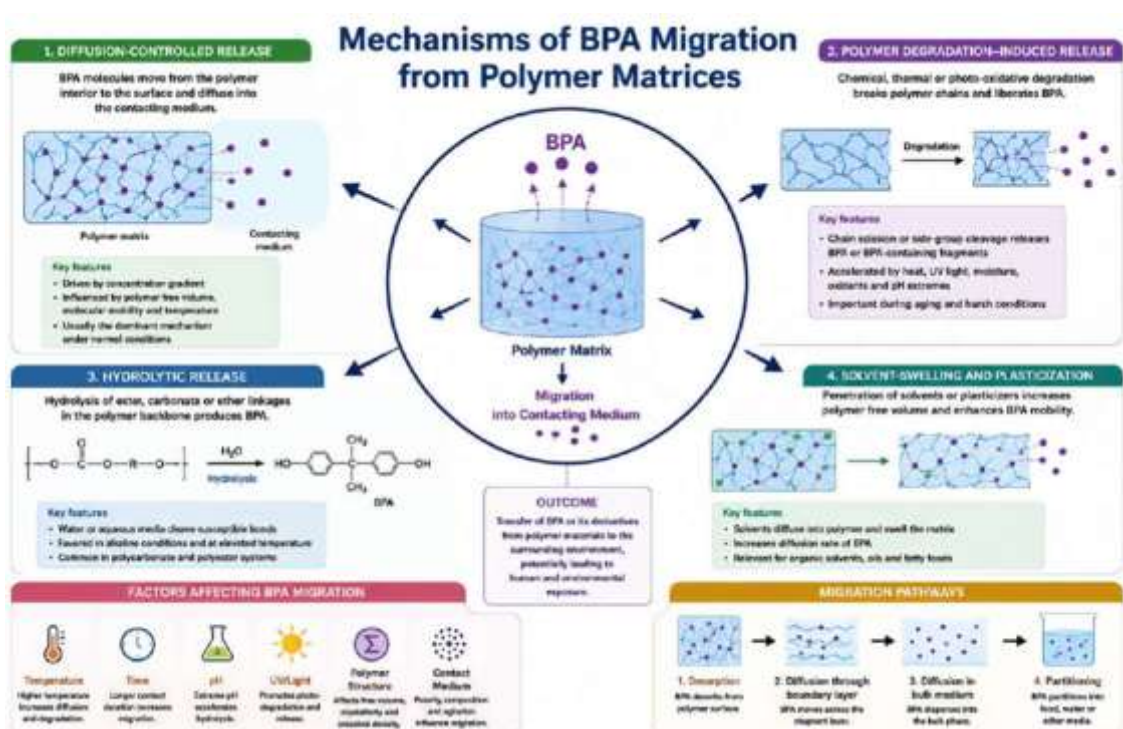


Figure: 3 Mechanisms of BPA Migration from Polymer Matrices

5. Analytical Approaches in Polymer

Accurately quantifying trace levels of BPA embedded within complex polymers requires highly sensitive extraction protocols. Common methods include matrix solid-phase dispersion or liquid-liquid extraction using organic solvents to swell the plastic network. Chromatographic analysis is conventionally handled via High-Performance Liquid Chromatography (HPLC) coupled with fluorescence detection, or Gas Chromatography-Mass Spectrometry (GC-MS) following chemical derivatization. To achieve real-time, highly selective

field testing, scientists are increasingly leveraging Molecularly Imprinted Polymers (MIPs)—synthetic receptors engineered with tailored cavities that lock onto target BPA molecules with high specificity (Alenazi et al., 2016).

6. Biological and Environmental Significances

Once liberated from its host matrix, BPA readily infiltrates aquatic ecosystems and terrestrial soil networks through industrial runtime discharges and landfill leachate (Datta et al., 2024). Biologically, its resemblance to natural steroid hormones allows it to

bind directly to estrogen receptors alpha (ER α) and beta (ER β), as well as membrane-bound G-protein coupled receptors (Cimmino et al., 2020). This binding action disrupts normal feedback pathways within the hypothalamic-pituitary-gonadal axis,

triggering reproductive toxicity, altered cell proliferation profiles, and systemic metabolic shifts across both wildlife populations and humans (Manzoor et al., 2022).

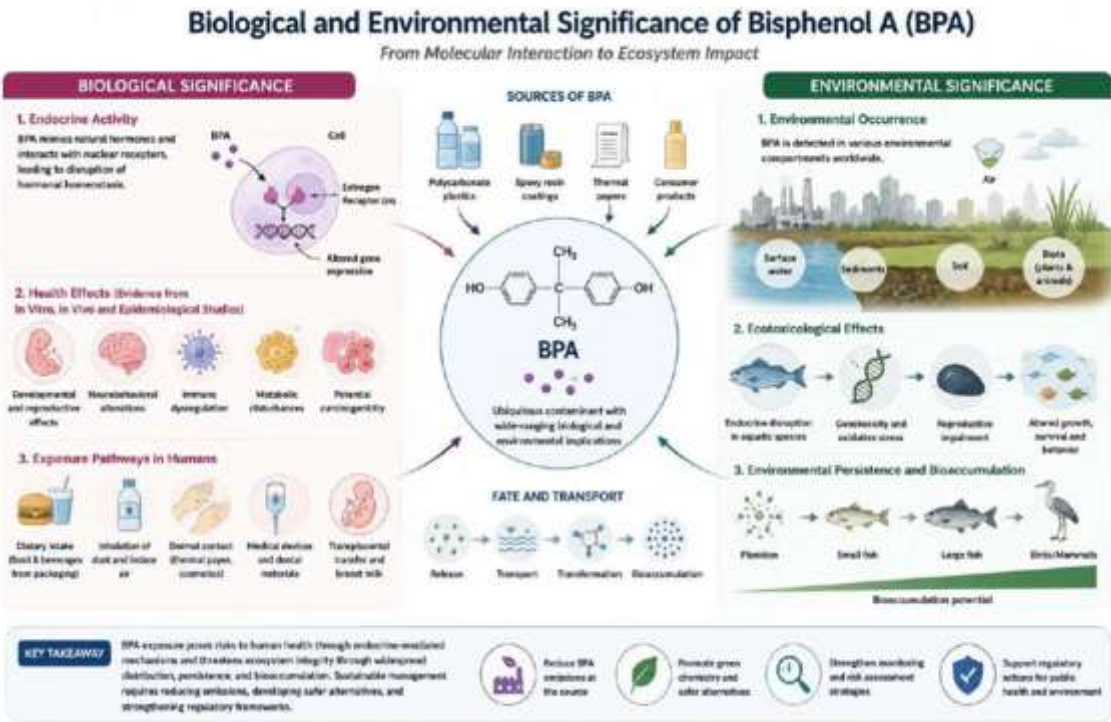


Figure: 4 Biological and Environmental Significances

7. Regulatory Consideration and Global Policy Development

Growing toxicological evidence has forced an international reassessment of safety standards. The European Chemical Agency (ECHA) classifies BPA as a Substance of Very High Concern (SVHC). Notably, Commission Regulation (EU) 2024/3190 has severely tightened restrictions on food-contact materials, catalysing an industry-wide transition

toward BPA-Non-Intent (BPA-NI) formulations, where BPA is actively excluded from raw material recipes to minimize trace contamination risks. Globally, frameworks fluctuate; while regions like the European Union, Canada, and specific US state agencies enforce strict specific migration limits (SML), other nations are still actively refining their regulatory mandates to balance industrial costs against public health protections (Datta et al., 2024).

Table: 1 Regulatory Consideration and Global Policy Development

Region/Country	Primary Regulatory Authority	Current Regulatory Position on BPA	Major Applications Affected	Regulatory Focus
European Union (EU)	European Commission; European Food Safety Authority (EFSA)	One of the most restrictive regulatory frameworks worldwide. BPA use in many food-contact materials has been substantially restricted, with phased implementation for affected products following Regulation (EU) 2024/3190. EFSA has also adopted a markedly lower	Food-contact plastics, epoxy can coatings, adhesives, coatings, varnishes, printing inks, and selected	Consumer protection, food-contact safety, endocrine-disruption risk reduction

		tolerable daily intake (TDI) based on updated toxicological evidence.	consumer articles	
United States (USA)	U.S. Food and Drug Administration (FDA); Environmental Protection Agency (EPA)	BPA remains permitted in several regulated applications where current exposure is considered acceptable by the FDA. Voluntary industry actions and specific prohibitions apply to infant bottles, Sippy cups, and similar products.	Food packaging, polycarbonate products, epoxy coatings, industrial materials	Exposure-based risk assessment and product-specific regulation
Canada	Health Canada	BPA has been prohibited in baby bottles, while exposure through food-contact materials continues to be periodically evaluated using updated scientific evidence.	Infant feeding products, food-contact materials	Protection of infants and vulnerable populations
Japan	Ministry of Health, Labour and Welfare	Significant reductions in BPA exposure have been achieved through industrial substitution and voluntary replacement in food-contact applications, supported by regulatory oversight.	Food cans, beverage containers, packaging materials	Preventive exposure reduction and industrial transition
China	National Health Commission (NHC) and related agencies	BPA use is regulated in food-contact materials with restrictions for infant feeding products and compliance requirements for migration limits.	Food packaging, infant products, polycarbonate materials	Product safety and migration control
India	Food Safety and Standards Authority of India (FSSAI); Bureau of Indian Standards (BIS)	BPA regulation is developing, with increasing attention to food-contact materials and children's products. Manufacturers are progressively adopting BPA-free alternatives for sensitive applications.	Food packaging, water bottles, consumer plastics	Food safety, harmonization with international standards
Australia & New Zealand	Food Standards Australia New Zealand (FSANZ)	Current assessments indicate that BPA exposure from approved food-contact uses remains within established safety limits, while ongoing monitoring continues.	Food containers, beverage packaging	Continuous scientific review and exposure monitoring

8. Challenges and Future Perspectives

The primary hurdle facing a complete phase-out of BPA is finding structural drop-in replacements that match its structural rigidity and chemical resistance without mirroring its toxicological profiles. Common substitutes, such as Bisphenol S (BPS) and Bisphenol F (BPF), are now facing similar scrutiny as studies reveal comparable endocrine-disrupting behaviour. Future research must pivot away from close structural analogues. Instead, focus should be placed on developing entirely distinct bio-based aromatic architectures derived from lignin, vanillin, or

cellulose-based matrices that offer clean degradation profiles.

CONCLUSION

The movement of bisphenol A (BPA) from polymer materials continues to be a complex issue, influenced by the aging of the polymer, the diffusion process through the material, and environmental temperature. Previously, efforts to reduce BPA release focused on improving the curing process to minimize free monomers. However, current toxicological standards now emphasize a shift in material design. To

effectively reduce overall exposure to BPA, it is essential to strictly apply manufacturing procedures that ensure BPA is not present in the final product, combined with ongoing research into developing non-toxic, plant-based materials.

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CONFLICT OF INTEREST

The authors state, they have no known competing financial interests or personal relationships that could affect the outcome of this research.

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