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Bisphenol A in Aquatic Environment: Occurrence, Environmental Fate, Ecotoxicology, and Management Strategies

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SUMMARY: The focus of this review is on four major issues: The presence, environmental fate and transport of BPA in surface water, groundwater, wastewater, sediments, and biota; the impact of BPA on aquatic organisms; cleanup strategies comprising monitoring, regulatory frameworks, treatment technologies, and remediation approaches; and finally, to pinpoint areas where there are knowledge gaps and directions towards future research. This scoping review was organised using the Arksey and O'Malley (2005) framework for scoping reviews. PubMed, Google Scholar, Web of Science and Scopus were searched systematically for peer-reviewed literature published between January 2005 and March 2026, over 200 journals were referred to, and 47 journals were cited after due consideration. During our search, it was established that Bisphenol A (BPA) is a chemical that is used extensively in the manufacturing of polycarbonate plastics, epoxy resins and a wide range of other items. BPA is an established pollutant of concern due to its endocrine-disrupting activities and its prevalence in the aquatic environments. It has gained a lot of attention. There is a need for an in-depth understanding of the fate of BPA in the environment, strategies for efficient removal, a more thorough understanding of BPA analogues, toxicity involving mixtures of pollutants, ecological effect on a long-term, and the effect of climate change on BPA distribution and fate.

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Bisphenol A (BPA; 2,2-bis(4-hydroxyphenyl) propane) is a synthetic chemical with the molecular formula of $C_{15}H_{16}O_2$ and a molecular weight of 228.29 g/mol. BPA was first sold in the 1950s and became one of the most widely used chemicals globally, with annual production exceeding 7 million metric tons (Wang *et al*., 2019). BPA is one of the fundamental components used in the production of polyethene plastics, medical equipment, epoxy resins, dental sealants, thermal paper and other industrial uses (Asenuga and Adeoye, 2023; Abdallah *et al*., 2008). One of the major challenges associated with the use of BPA has to do with it being an established endocrine-disrupting compound (EDC), which is capable of causing hormone imbalance even at very minute quantities. There are estrogen-like effects when BPA binds to estrogen receptors, resulting in hormonal disorders in both wildlife and people (Kang *et al*., 2007; Matuszczak *et al*., 2019). BPA is widely present in the aquatic habitats globally due to its extensive usage, incomplete removal during the processing of wastewater and its persistence in several ecological biomes (Fu and Kawamura, 2010). As a result of the established detrimental effect of BPA on human health and the ecosystem, there are growing concerns about the impact of BPA on the aquatic environment. BPA

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and its similar compounds, such as Bisphenol S (BPS) and Bisphenol F (BPF), can be found in surface waters, wastewater, groundwater, sediments, discharges, and aquatic organisms (Gil-Solsona *et al.,* 2022). The discovery of BPA at different levels from nanograms to micrograms per litre in so many water sources resulted in several regulatory bodies creating global policy frameworks and restrictions on BPA usage in consumer items. There are several studies on BPA presence, understanding its ecosystem interplay, ecological effects, and creating effective removal solutions. Recent studies focus on the fate and the effect of BPA analogue, climate change influence on BPA distribution, advanced methods for the removal of BPA and creating predictive models for evaluating its environmental fate (Fu and Kawamura, 2010). This review gathers information for a better understanding of BPA in the aquatic environments, addressing prevalence patterns, ecotoxicological processes, as well as its impacts and strategic planning, while acknowledging important information gaps needing more research.

METHODOLOGY

This review was written systematically via a meticulous, structured exploration of peer-reviewed literature on BPA in the aquatic environment using the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension (PRISMA-ScR) for scoping reviews. A comprehensive literature search was conducted across multiple electronic databases to ensure broad coverage of relevant peer-reviewed literature from 2005 to 2026 across PubMed/MEDLINE, Scopus, Wiley Online Library, ScienceDirect, Google Scholar, ACS Publications, SpringerLink, Web of Science, and RSC Publishing. The search plan includes terminologies and search terms associated with Bisphenol A, aquatic pollutant, bioremediation, phytoremediation, environmental pollutants, environmental contaminants, and regulatory framework in the aquatic bodies. Research papers that were included were original research, reviews, or conference papers published in peer-reviewed sources that focused on the specified search terms and were excluded if they were focused exclusively on other chemicals in the aquatic environment aside from BPA. The scope of this review covers four major focus areas, these include (1) The presence, environmental fate and transport of BPA in surface water, groundwater, wastewater, sediments, and biota (2) the impact of BPA on aquatic organisms, (3) cleanup strategies comprising monitoring, regulatory frameworks, treatment technologies, and remediation approaches, and (4) finally to pinpoint areas where there are knowledge gaps and directions towards future research. This methodology ensured an organised, transparent, and replicable approach to identifying, choosing, and integrating the peer-reviewed literature on BPA in the aquatic environment, providing a substantial basis for the comprehensive review presented.

BPA Occurrence in Aquatic Environments: The pollution of water in various geographical areas and types of water bodies occurs through specific and general sources such as industrial releases, farm runoff, urban wastewater, leakage from plastic items, and dumps. (Nishmitha *et al*., 2025).

Aquatic Biota: Due to BPA's metabolic change and excretion pattern, bioconcentration factors (BCFs) are typically low to moderate (usually <1000) despite evidence of BPA bioaccumulation in aquatic life across various trophic levels (Naomi *et al.,* 2022). BPA can be absorbed by Invertebrates such as molluscs and crustaceans, and the amounts absorbed are dependent on the exposure levels, removal rates, species-specific uptake and environmental factors. In the fish tissue, BPA levels range from <10 to several hundred nanograms per gram wet weight, with higher amounts often found in fish obtained from polluted areas (Naomi *et al.,* 2022). The presence of BPA in aquatic animals is of growing concern not only because of the ecosystem health but also for human health, because eating contaminated fish and shellfish can lead to the accumulation of BPA in the human body.

Surface Water: Landscape heterogeneity showed that there are higher amounts of BPA in surface waters near industrial areas, cities, and wastewater treatment plant (WWTP) discharge points. High BPA concentrations have been observed in surface waters as a result of increased industrial growth and dense populations in Asian countries, mainly China and India (Huang *et al*., 2011). Mishra *et al*. (2021) investigations showed that BPA detection rates in surface water are less than 10 ng/L in clean regions; in highly polluted environments such as industrial and urban watersheds, it is greater than 1000 ng/L. BPA concentration in surface water can be affected by seasonal shifts because of flow rates, as higher concentrations are observed during reduced flow times when the capability to dilute is decreased.

Sediments and Sludge: BPA has an average hydrophobicity and can move from the water phase to sediments and suspended particles, therefore making sediments an important repository and can be a secondary pollution source. BPA levels in Sediment vary from less than 1 ng/g dry weight (dw) in reference sites to greater than 1000 ng/g dw in heavily industrialised locations (Tijana and Tom, 2021). Several factors, including organic carbon content, particle size distribution, pH, and redox conditions, determine the level of BPA accumulated in sediments. Elevated levels of BPA can be observed in wastewater treatment sludge, which is often over 1 mg/kg dw due to sorption during the treatment processes (Ighalo *et al.,* 2024).

Wastewater and Effluents: The main route through which BPA get into the water bodies is industrial and urban effluents. Studies have shown that BPA levels between 1 and 30 g/L have been found in raw wastewater, which are contributed from personal care items, thermal paper, household products, and industrial activities (Graziani *et al*., 2019). Complete removal of BPA from wastewater is difficult, even with standard wastewater treatment methods; only about 50-90% BPA can be removed, resulting in BPA effluent levels of 0.01-5 g/L. The efficiency of the standard wastewater treatment is dependent on factors such as time, temperature, hydraulic retention time, sludge age, and the treatment technology used. The use of advanced wastewater treatment procedures, such as membrane bioreactors, ozonation, and advanced oxidation processes, leads to higher removal capacities greater than 95%, but their uses are limited to a few locations. Therefore, the major contributors to the BPA level in surface water are wastewater treatment plant discharges.

Groundwater: The consistent presence of BPA in groundwater is an important concern about long-term contamination, especially in aquifers that provide drinking water. BPA reaches the groundwater by seeping from landfills, blending with contaminated surface water, and through the use of treated wastewater for irrigation processes (Tiehm *et al*., 2012). BPA levels in groundwater range from the minimum concentration to several hundred nanograms per litre; it is lower than surface water levels due to attachment to aquifer materials and microbial breakdown in anaerobic conditions (Tiehm *et al.,* 2012).

Environmental Fate and Transport: Understanding the environmental fate and transport of BPA is essential to deduce its level and duration of impact as well as the possible routes of exposure in the aquatic ecosystems. Several interacting processes, such as segmentation among ecosystem constituents, conversion through biotic and abiotic means, and transportation through water, sediment, and organisms, determine the action of BPA in the aquatic environments (Hahladakis *et al*., 2018).

Biological Degradation Processes: Biological degradation of BPA is the major way BPA is eliminated in several water bodies. BPA degradation through the aerobic route is faster, with half-lives ranging from hours to days, is faster compared to the anaerobic degradation route that takes weeks to months (Jaime *et al*., 2022). Several groups of bacteria are capable of breaking down BPA. These bacteria have been found in the soil, wastewater, and aquatic sediments, those bacteria species include genera Pseudomonas, Sphingomonas, Bacillus, and Novosphingobium. Breakdown of BPA in aerobic conditions begins with the hydroxylation of the aromatic rings, then involves ring opening and breaking down into carbon dioxide and water. Cytochrome P450 monooxygenases and several ring-cleaving dioxygenases are biological catalysts involved in the degradation of BPA (Jaime *et al*., 2022). Under anaerobic conditions, BPA breakdown occurs via several means bit by bit, with methanogenic and sulfate-reducing environments allowing some BPA changes, though complete degradation of BPA under anaerobic conditions is not well documented. Using BPA-degrading bacteria for bio-remediating procedures has demonstrated potential for managing contaminated waters and sediments (Sultana *et al*., 2024). Understanding the factors that affect the rates of BPA biodegradation is essential for improving bioremediation procedures; these factors include nutrient levels, microbial community structure, temperature, availability of oxygen, pH, and the interference from other pollutants that might prevent degradation.

Absorption and Partitioning: The partitioning of Bisphenol A between water and solid materials alters its fate in the environment and bioavailability. BPA was moderately soluble and is capable of adhering to the sediments, soil organic matter, and floating particles. Environmental conditions such as ionic strength, pH, and temperature determine the absorption process. There are two phenolic hydroxyl groups in BPA, and it has a pKa of about 10.2, suggesting that at pH levels between 6 and 8, it will exist mainly in its neutral, more hydrophobic state, promoting sorption to organic matter. While at higher pH levels, the loss of protons makes BPA more water-soluble and reduces sorption. Recently, multimedia modelling research has used the partitioning behaviours of BPA to predict the distribution of BPA across water, sediment, and living organisms in aquatic microcosms, which enables researchers to further understand BPA's environmental behaviour (Im and Löffler, 2016).

Abiotic Transformation: Abiotic transformation processes such as photolysis, chemical oxidation, and hydrolysis, facilitate the removal of BPA from water, but not as efficiently as biodegradation. Photodegradation can take place directly by absorbing UV light or indirectly through natural photosensitising agents like dissolved organic matter, iron species, and nitrate (EPA, 2013). Factors such as light intensity, water depth, turbidity, and the existence of photosensitizers determine photolysis half-lives in surface waters, which range from hours to days (Luca *et al.*, 2025). The involvement of reactive oxygen species, for example, hydroxyl radicals, peroxy radicals, and singlet oxygen in chemical oxidation through photochemical or other methods can break down BPA into various oxidation products. Improved oxidation procedures, such as UV light, ozone, and hydrogen peroxide, can break down BPA in engineered treatment systems rapidly. The use of hydrolysis for the degradation of BPA is negligible under normal environmental pH and temperature due to the chemical stability of BPA (Anhong *et al.*, 2022).

Multimedia Fate Modelling: Multimedia fate models are essential tools for combining the several processes that determine BPA distribution and predicting its fate among related environmental compartments. Fugacity-based models and key simulation methods are currently being used to demonstrate BPA partitioning among water, suspended particles, sediment, and organisms in the aquatic environment (MacLeod *et al*., 2010). These models utilise degradation rate constants, partitioning coefficients, transport parameters and physicochemical properties to forecast BPA actions in different situations. The applications of these models have enhanced the understanding of major processes, the duration and distribution of BPA in water habitats (MacLeod *et al*., 2010). Major findings lay emphasis on the importance of biodegradation in impacting overall BPA lifespan, the fact that sediments serve as both sinks and possible indirect sources, and the impact of water duration on BPA concentration in receiving waters. In the future, modelling methods should be developed to include various BPA analogues, climate change scenarios, and better parameters that can assess degradation rates. This will enhance predictions of BPA's environmental behaviour.

Ecological Toxicology in Aquatic Systems: The negative effect of BPA on organisms in the water bodies has been deeply researched, showing biological impact at various levels, from population and community levels to molecular and cellular levels. BPA, an established endocrine disruptor, alters hormonal signalling pathways, resulting in various detrimental impacts on development, reproduction, growth, and survival (Wu and Seebacher, 2020).

Sub-Lethal Physiological Effects: Studies have shown that several harmful but not deadly physiological impacts that can affect the fitness of individuals and populations have been attributed to BPA. BPA can have neurotoxic effects, such as reduced swimming ability, erratic behaviour, and alteration of the neurotransmitter systems (Inadera, 2015). It has been observed that exposure to BPA can lead to oxidative stress, lipid breakdown, Immunotoxic effects such as changes in immune cell numbers, reduced ability to engulf pathogens, and reduced resistance to disease, as well as disruption of metabolism, evident by disturbance of energy storage, alteration of metabolic gene expression and lipid profiles, in various aquatic species. These harmful impacts can affect an organism's fitness, enhance the risk of illness and predation, and definitely affect population growth, especially when combined with other environmental stressors (Cimmino *et al*., 2020).

Mixture Toxicity and Real-World Exposure Scenarios: Aside from bisphenols, aquatic organisms are also exposed to other contaminants like drugs, pesticides and industrial chemicals. Research has shown both additive and non-additive effects, making risk evaluation more challenging (Singh *et al*., 2025). Field research evaluating the health of aquatic organisms in BPA-contaminated environments has provided proof connecting lab results to actual impacts. The use of several biomarkers in BPA-polluted areas indicates signs of endocrine disruption in wild fish populations, which include increased vitellogenin levels in males, alterations in sex hormone levels, and inter-sex conditions. Combined exposure to BPA and other endocrine disruptors interferes with reproductive outcomes that surpass additive levels, even when the concentration of individual chemicals is below their effect thresholds (Maroua *et al*., 2023). Therefore, associating these alterations solely to BPA without considering other pollutants is tricky, indicating the need for improved approaches to determine risks associated with chemical mixtures and to determine the cause-and-effect links in complex real-world conditions (Kumar *et al*., 2020; Peskova and Blahova, 2025).

Reproductive Health Effects: Reproductive toxicity is a well-known effect of BPA in aquatic organisms, with several studies pointing to variation in gonadal development, alteration in sex ratios, reduced fertility, and changes in reproductive behaviour following exposure to BPA during the main developmental periods in fish (Zuchun *et al*., 2024). Model species such as Medaka (Oryzias latipes), fathead minnow (Pimephales promelas) and zebrafish (Danio rerio) have been studied, following reproductive effects at concentrations as low as 1-10 g/L were observed (Onishi *et al*., 2021; Zuchun *et al*., 2024). Teratogenic effects such as delay in hatching, reduced rate of survival in early life stages, deformation of the skeletal system, and changes in growth patterns have been noticed in fish, invertebrates and amphibians. (Zuchun *et al*., 2024) following exposure to BPA. However, amphibians are more susceptible to BPA during metamorphosis, with studies showing disorderliness in thyroid hormone signalling, delayed metamorphosis, and modification in body size at metamorphic climax. With Daphnia species and aquatic insects, reproductive and developmental effects include lower fecundity, changed moulting, and slowed population growth (Metruccio *et al*., 2024; Zuchun *et al*., 2024).

Management Strategies for BPA Pollution: Controlling BPA pollution effectively in the coastal zones requires multiple procedures comprising a regulatory framework, avoiding pollution, monitoring, treatment procedures, and cleanup methods. Recently, significant progress has been observed in all the above-listed strategies, though their application differs globally.

Monitoring and Assessment Frameworks: Extensive surveillance programs are important for gaining deeper insights into BPA pollution, ascertaining the sources, observing trends over time, and determining the outcome of management actions. The use of advanced analytical techniques, especially liquid chromatography-mass spectrometry (LC-MS/MS), enabled low-level detection of BPA and its variants (pg/L to ng/L) in several environmental samples (Xingyu *et al.,* 2024). Polar organic chemical integrative samplers (POCIS), which are a passive sampling procedure with semipermeable membrane devices (SPMDs), are fundamental tools for continuous surveillance. The combination of environmental effect assessment frameworks and data monitoring with ecotoxicological details is used to report the results. The ratio of observed environmental levels to predicted no-effect levels (PNECs), known as Hazard quotients, is usually employed to evaluate ecological impact (Andrea *et al*., 2018). Ongoing evaluations have highlighted particular regions and ecological sections in waterbodies where BPA levels might jeopardise the health of aquatic organisms, so that management efforts might be prioritised.

Regulatory Policies and Guidelines: Regulatory measures for the use of BPA have been determined by several regions, as well as setting water quality guidelines. The use of BPA in thermal paper and some consumer goods has been limited by the European Union due to the fact that BPA has been tagged as a substance of distress (Robert *et al*., 2020). The European Union has set a standard for BPA in surface waters to be 1.5 g/L (annual average); however, in other regions, different limits have been established on community risk assessment. Under the Canadian Environmental Protection Act, BPA has been established as toxic, and its use in baby bottles has been banned (Jianchao *et al*., 2021). In the United States, the use of BPA has also been limited in baby necessities and packaging materials, although comprehensive federal regulations are still lacking. Various governing bodies have established water quality regulations and environmental criteria for BPA, though there are still differences in the values (Yu *et al*., 2019). The regulatory strategies are constantly developing as new data from toxicological studies appear and apprehension regarding BPA analogues grows, with regulation on the use of bisphenol substitutes alongside BPA emerging in some regions.

Wastewater Treatment System: The intentional removal of BPA during the treatment of wastewater represents an important strategy for minimising the inflow into the aquatic environment (Feng *et al*., 2024). Conventional activated sludge processes attain 40-90% removal of BPA through biological degradation and sorption to sludge, with process optimisation depending on operational parameters such as hydraulic retention time, solids retention time, and temperature (Feng *et al*., 2024). Membrane bio-catalyst (MBRs) usually achieve an 80-95% removal efficiency (due to complete biomass retention and longer solids retention times (Feng *et al*., 2024). The elimination capacity of BPA was increased with advanced treatment processes. BPA was productively degraded using Ozonation through oxidation with >90% removal efficiencies obtainable at ozone doses of 2-5 mg/L (Liu *et al*., 2018). The use of advanced oxidation processes together with ozone and hydrogen peroxide or UV irradiation can result in almost-complete BPA removal efficiency. Powdered and granular activated carbon used in the activated carbon adsorption process removes BPA from water successfully via periodic regeneration. Nanofiltration and reverse osmosis membranes are capable of achieving >95% BPA removal, the process is expensive, with concentrate disposal challenges limiting the widespread use of these processes (Feng *et al*., 2024). The consideration of treatment objectives, water quality characteristics, influent BPA concentrations, energy requirements, operational complexity and costs is required by several appropriate treatment procedures. The merging of hybrid approaches, biological treatment with advanced oxidation or adsorption processes, may offer cost efficiency for many operations.

Source Control and Pollution Prevention: The strategies to prevent pollution aim to reduce BPA releases at the source, showing the most eco-friendly strategic approach to pollution control (Sourav *et al*., 2025). Product exchange, substituting BPA-containing materials with lower-risk options, has found support in consumer products, thermal paper applications and food packaging. However, choosing alternative materials demands a thorough assessment to prevent choosing compounds with comparable or significant risks (Sourav *et al*., 2025). Industrial source control measures such as modification of processes aimed at reducing the use and release of BPA, pre-treatment systems installation at industrial facilities before the release of industrial waste to municipal sewers, and the adoption of excellent management practices for the oversight of BPA-containing materials (Hassimi *et al*., 2023). The establishment of programs that make manufacturers responsible for the final handling of BPA-containing products has been enacted in some jurisdictions to enhance collection and appropriate disposal (Hassimi *et al*., 2023). Campaigns advocating for consumers to minimise their use of BPA-containing products, promoting organised disposal, and supporting eco-friendly utilisation patterns, all enhanced regulatory and technology-driven solutions. The complete adoption of green chemistry principles, which emphasises the development of naturally much safer chemicals and production processes, will offer a structure for the development of next-generation materials that prevent or minimise the pitfalls of BPA and current analogues (Hassimi *et al*., 2023).

Environmental Remediation Approaches: Several remediation innovations have been researched for cleaning up contaminated aquatic sediments and water bodies. Bioremediation techniques using naturally occurring or augmented microorganisms that can degrade BPA are showing potential as eco-friendly treatment strategies (Narendra *et al*., 2024). Bioaugmentation procedure using isolated BPA-degrading bacterial strains and bio-stimulation procedure that involves nutrient addition to enhance initial pollutant degrader populations have shown competence in laboratory and pilot-scale studies, although large-scale applications will entail further optimisation (Rehman *et al*., 2021). The use of aquatic plants that have the ability to absorb BPA and transform it (Phytoremediation) is another biological technique under investigation. Constructed wetlands created for BPA removal have exhibited the capability for treating polluted waters and low-strength wastewater. Engineered approaches such as isolation of contaminated sediments using sediment capping, dredging and ex-situ handling, and chemical oxidation in situ have been planned for extremely contaminated sites, though applications solely for BPA-polluted sites are limited when related to other priority pollutants (Narendra *et al*., 2024). Several procedures, such as advanced nanomaterials for BPA uptake and breakdown, photocatalytic systems for solar-driven BPA conversion, and enzymatic treatment procedures using immobilised oxidative enzymes, are all upcoming remediation technologies in progress. Laboratory implementation of these techniques shows promise, though field implementation and cost effectiveness are required before extensive adoption.

Research Gaps and Future Directions: Regardless of significant research advancement over the past decade, a significant deficit in knowledge still exists concerning the presence of BPA in aquatic environments. Managing these knowledge deficits is crucial for thorough risk assessment and the improvement of effective strategy execution.

BPA Analogues and Transformation Products: The substitution of BPA with structural analogues, which include BPF, BPS, BPAF, etc., requires a thorough understanding of their toxicity, behaviour in the environment, and risks, which is of extreme importance. Latest findings suggest that some of the BPA analogues also have similar or superior persistence, endocrine-disrupting activity, and bioconcentration potential when compared to BPA (Neri *et al*., 2024). This suggests that substitution alone can't eradicate environmental and health concerns. Thorough evaluation of all bisphenol analogues currently in use, their breakdown products, and potential for mixture effects requires immediate attention. In addition, breakdown products obtained during the degradation of BPA via photolytic, biological, or chemical oxidation processes require scrutiny. It is assumed that degradation of the parent compound is associated with reduced toxicity, though studies have shown that some degradation products can possess or even demonstrate enhanced biological activity (Cheng and Wang, 2024). The quantification, toxicological characterisation, and systematic identification of BPA breakdown products in environmental samples remain deficient.

Mixture Toxicity and Multiple Stressor Interactions: Concurrently, aquatic species are exposed to heterogeneous mixtures of chemicals and several environmental stressors. Understanding the interactions of BPA with co-occurring pollutants and natural stressors in affecting the health of aquatic organisms is an essential knowledge gap that needs to be studied. Individual chemical testing is the sole basis of study for current risk assessment frameworks of BPA, which essentially underestimate cumulative risks involving other chemicals. The emergence and confirmation of models for mixture toxicity and procedures for evaluating multiple stressor situations would be beneficial for accurate assessment of ecological risk (Salia *et al.*, 2025)

Long-Term And Population-Level Effects: Most environmental toxicological studies on BPA are usually short-term chronic exposures in a controlled laboratory environment. Prolonged, transgenerational and population-level effects of chronic exposure to low-level BPA in normal aquatic ecosystems are poorly defined. Inter-generational effects, in which consequences observed following exposure to BPA in one generation affect succeeding generations even without direct exposure, should be studied in both laboratory and field conditions (Tan-Duc *et al*., 2025). The integration of sub-lethal effects on growth, survival, and reproduction following exposure to BPA using population modelling methods is essential to insights into population-level implications, though comprehensive empirical data is required.

Climate Change Implications: The distribution, effects and fate can be altered by climate change via several Pathways. BPA degradation rates can be affected by high temperature, which leads to acceleration of biological degradation, but volatilisation is increased, and partitioning behaviour will be altered (Mengxin *et al*., 2025). The transportation and dilution of BPA in the aquatic system can be modified in the aquatic system with changes in rainfall trends, alteration in hydrological regimes and drastic weather phenomena. Toxicity attributed to some chemical which was temperature dependent have been discovered, suggesting that the toxicity associated with BPA can also be temperature-sensitive. In addition, physiological stress induced by climate change in aquatic animals may alter their sensitivity to BPA following exposure (Jing *et al*., 2019). Therefore, the assessment of these climate-pollutant interactions should represent a new research frontier.

Advanced Treatment Technology Optimisation and Implementation: The evaluation of BPA environmental footprints using comparative life cycle analysis. The feasibility of various treatment possibilities would help to determine the technology to select. Though several advanced treatment innovations have shown high efficiency of BPA removal in the laboratory and following pilot studies, knowledge gaps still exist concerning several factors, such as varied water quality conditions, operational challenges, prolonged performance, and cost effectiveness at full scale (Sheikh *et al*., 2018). In addition, studies on energy-saving processes, recovery of resources from treatment systems, and waste management (e.g., spent adsorbents, concentrated waste streams) would improve the long-term viability of treatment.

Innovative Monitoring and Detection: Advances in analytical methods would allow rapid, economically feasible, and flexible field detection of BPA and its analogues, which would strengthen the regulatory framework. The development of biosensors, immunoassays, and other portable field detection technologies would allow for more temporally and spatially comprehensive monitoring (Shah *et al*., 2023). The combination of effect-based monitoring procedures with chemical analysis would improve the evaluation of biological relevance and additive effects of chemical mixtures.

Source Apportionment and Mass Balance Studies: The BPA sources, pathways, and sinks at watershed and regional scales broad understanding that would inform targeted management interventions. Source allotment studies using isotopic techniques, chemical fingerprinting, or statistical modelling could be employed to determine principal BPA sources in precise systems (Cimmino *et al.*, 2020). Mass balance studies are used for tracking BPA inputs, transport, transformation and outputs, which would enhance a comprehensive understanding of system-scale fate and to recognise important control points (Dan *et al*., 2025). Such research involving harmonize monitoring programs, hydrological modelling, and a combination of data across multiple environmental compartments.

Conclusion: This review extensively discusses the presence of BPA, its fate, toxicity and numerous management strategies. The growing awareness of the effects of the mixture of chemicals and several stressor interactions highlights the limitations of single-chemical risk assessment procedures and requires a more integrated approach.

Constant surveillance, research, and adaptive management will be important as new obstacles emerge and understanding unfolds. Upcoming research priorities should put a spotlight on BPA analogues and their transformation products, mixture toxicity under multiple stressor conditions, climate change interactions, long-term population-level consequences, and development of eco-friendly, affordable treatment and remediation technologies.

DECLARATION

Ethical Approval: There was no involvement of human participants or animal experimentation, so there was no need for formal ethical approval. All techniques involving data management and assessment were carried out responsibly and in compliance with standard academic and institutional guidelines

Disclaimer on Artificial Intelligence usage: We did not use any generative Artificial Intelligence (AI) technologies during writing or editing of this manuscript.

Conflict of Interest: All authors declare that there is no competing financial interest or personal relationship with other people or organisations that could inappropriately influence this manuscript.

Declaration of Data Availability: The First author is responsible for making all data used in this research available upon request from the

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