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Corals as Chemical Archives: PAH Concentration, Transformation, and Ecosystem Risk Across the Tropical Belt

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Abstract

Polycyclic aromatic hydrocarbons (PAHs) are now widespread and consequential contaminants in tropical and subtropical coral reef ecosystems. Studies from the Arabian Sea, South China Sea, Brazilian Atlantic, Persian Gulf, Gulf of Suez, and remote oceanic archipelagos show that PAHs permeate seawater, suspended particulates, sediments, island soils, coral tissues, mucus, Symbiodiniaceae, benthic invertebrates, and reef fishes. Although many concentrations fall within regulatory categories labeled low to moderate, experimental and field data reveal physiological impairment, bioaccumulation, trophic transfer, and metabolic stress at levels below existing environmental thresholds. Multi-matrix comparisons demonstrate large heterogeneity, with particulates and biological tissues showing orders-of-magnitude enrichment over dissolved fractions. Extreme particulate loads reported from Lakshadweep lagoons (6469.86 ng g^{-1}) and high concentrations in Persian Gulf coral tissues (1127 ng g^{-1}) and zooxanthellae (1421 ng g^{-1}) indicate that corals and symbionts act as biochemical concentrators. Atmospheric deposition, including gas-phase PAHs up to 113.1 ng m^{-3} in offshore South China Sea reefs, highlights long-range transport independent of local industry. Experimental research also shows sensitivity in early life stages and symbioses, including coral-larval impairment at ~34 µgTAHL^{-1} and fossil-carbon assimilation by Symbiodiniaceae under crude-oil exposure. Briefly, PAHs represent chronic ecosystem-level stressors with major implications for coral-reef resilience under accelerating climate pressure.

Keywords: coral reefs, PAHs, bioaccumulation, trophic transfer, biomarker

INTRODUCTION

Coral reef ecosystems represent one of the most chemically dynamic and ecologically sensitive environments on Earth. Distributed broadly across tropical and subtropical latitudes, these ecosystems support more than one quarter of marine biodiversity and sustain essential ecosystem services including shoreline protection, fisheries productivity, carbon cycling, and coastal economies (Monchanin *et al.,* 2025; Liao and Chen, 2025; Veettil and Puri, 2025). Despite their ecological prominence, coral reefs face intensifying pressures from cumulative anthropogenic stressors, particularly contamination from petroleum- and combustion-derived polycyclic aromatic hydrocarbons (PAHs). Over the last decade, PAHs have shifted from being considered peripheral contaminants to becoming structurally embedded components of reef stress regimes (Yang *et al*., 2020; Han *et al*., 2022; He *et al*., 2025). Their persistence, hydrophobicity, and toxicological potency elevate concerns regarding chronic exposure pathways, bioaccumulation, and long-term ecosystem-scale consequences (Xiang *et al*., 2018; Cao *et al*., 2024; Cao *et al*., 2025).

Increasing industrialization, maritime traffic, nearshore oil storage and refining, coastal development, and deposition of atmospheric combustion residues collectively fuel the input of PAHs into coral reef systems. Once introduced into the marine environment, PAHs are partitioned across multiple compartments including dissolved and particulate seawater, sediments, soils, coral tissues, mucus layers, and associated microbiomes and symbionts (Morison *et al*., 2013; Menezes *et al*., 2024; Lima *et al*., 2025). This complex compartmentalization shapes spatial gradients of contamination and exposes multiple trophic levels to differential risk. Furthermore, PAHs undergo intricate biogeochemical transformations influenced by photodegradation, microbial

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metabolism, and physicochemical conditions, generating derivative products such as oxygenated and nitrated PAHs that often exhibit greater bioavailability and toxicity (Chen *et al*., 2023a; He *et al*., 2025). Consequently, a comprehensive understanding of PAH dynamics in coral reef systems requires integrated analysis of concentration patterns, transformation mechanisms, and ecological impacts across temporal and spatial scales.

Recent studies have advanced baseline knowledge on PAH occurrence in tropical reefs across the South China Sea, the Arabian Sea, the Brazilian Atlantic, and the Persian Gulf, highlighting significant heterogeneity among environmental matrices (Oladi and Shokri, 2021; Nordborg *et al*., 2022; El-Alfy, 2024; Qiu *et al*., 2024; Cao *et al*., 2025; Mello *et al*., 2025). However, most existing research remains fragmented, frequently constrained to snapshot monitoring of dissolved-phase or sedimentary PAH concentrations without evaluating multi-compartment interactions or transformation pathways. This limitation restricts the interpretation of exposure dynamics, especially where rapid exchange processes occur between seawater, suspended particulates, coral tissues, and mucus interfaces. Coral mucus in particular represents a unique microenvironment where hydrophobic contaminants accumulate and interact with symbiotic dinoflagellates (*Symbiodiniaceae*), microbiomes, and early life stages such as recruits and larvae (Renegar *et al*., 2017; Li *et al*., 2021). Yet, mechanistic exploration of these interaction zones remains significantly under-represented in global assessments.

A clearer synthesis is further hindered by narrow species-level focus in many studies, which prioritize scleractinian taxa but rarely include octocorals, reef sponges, mollusks, seagrass communities, or grazers and predators within reef food webs. This taxonomic confinement produces an incomplete picture of PAH trophodynamics and risks underestimating ecosystem-scale consequences. For example, PAH burdens recorded in coral tissues generally fall within intensity ranges still categorized by regulatory frameworks as low to moderate contamination (Cui *et al*., 2026 ; Menezes *et al.,* 2024 ; Vignesh *et al*., 2024). Nevertheless, empirical evidence from physiological and molecular experiments demonstrates pronounced sublethal impacts including oxidative stress, immune suppression, symbiont expulsion, metabolic disruption, reduced reproductive success, and growth suppression at concentrations far below existing regulatory thresholds (Nordbrog et al., 2022; Morris *et al.,* 2019). These findings highlight the inadequacy of concentration-based risk labeling and emphasize the need for integrated ecological-process evaluation. Several recent reviews contributions provide valuable groundwork but reveal explicit scientific gaps that demand resolution. For instance, Nalley *et al*., (2021) and Menezes *et al*., (2023) presented important datasets on PAH contamination and responses of scleractinian corals in tropical regions; however, their analyses largely relied on general water quality indicators and single-species physiological responses, remaining detached from broader biophysical mechanisms. Furthermore, both studies prioritized static water-column chemistry and localized species sensitivity, without incorporating oceanographic drivers such as hydrodynamic mixing, upwelling, mesoscale eddies, river plumes, estuarine retention, or wind-driven circulation. These physical processes strongly determine pollutant transport, residence times, deposition, resuspension, and spatial gradients on coral reefs. Consequently, interpreting PAH contamination patterns without incorporating oceanographic structure risks misrepresenting the origin pathways, transport connectivity, and ecological exposure frameworks.

Similarly, the absence of temporal resolution in many prior studies limits understanding of how episodic events such as monsoons, storms, cyclones, internal waves, and sediment resuspension pulses influence PAH availability and toxicity. Evidence from recent field campaigns indicates that particulate reservoirs often contain orders-of-magnitude higher PAH loads than dissolved fractions (Jesus *et al*., 2022; Rabodonirina *et al*., 2015), amplifying exposure risk during high-energy events or sediment disturbance. Without integrating ecosystem-scale hydrodynamics and seasonally stratified monitoring, our capacity to evaluate true risk trajectories remains constrained.

Recognizing corals as chemical archives capable of integrating long-term contamination histories across skeletal and tissue structures offers a transformative pathway to reconstruct PAH exposure patterns. Corals accumulate persistent organic pollutants and record temporal variations within growth bands, analogous to tree rings or glacial ice cores. This inherent archival capability enables retrospective analysis of anthropogenic pressure, ecological regime shifts, and the coupling between chemical exposure and reef decline. When combined with modern analytical instrumentation such as GC-MS/MS, LC-MS/MS, and stable-isotope frameworks, coral archives provide unprecedented opportunities to characterize both current and historical PAH trends and establish mechanistic links between oceanographic forcing and contaminant dynamics.

This article synthesizes current global knowledge on PAH concentrations, transformation processes, trophic transfer, and ecosystem risk across tropical coral reefs, highlighting the critical need to integrate multi-matrix chemical analysis, archival coral records, biological response indicators, and oceanographic transport dynamics. Addressing the unfilled gaps identified in prior research is fundamental to developing predictive models of contaminant transport, strengthening environmental risk frameworks, and informing ecosystem-level management strategies essential for the future resilience of coral reef systems.

This review consolidates and interprets current scientific understanding of polycyclic aromatic hydrocarbons (PAHs) in coral reef ecosystems by synthesizing spatial patterns, concentration ranges, and dominant pollutant profiles across multiple environmental matrices and globally distributed reef locations. By integrating data from dissolved and particulate water fractions, sediments, reef-island soils, coral tissues, mucus, symbiotic algae, benthic invertebrates, and reef fishes, the review aims to clarify the principal sources, partitioning behavior, atmospheric and hydrodynamic transport pathways, and reservoir dynamics that govern PAH distribution in both industrialized and ostensibly remote reef settings. In doing so, the review evaluates the role of biological compartments such as coral tissues and zooxanthellae as biochemical PAH concentrators, and assesses trophic amplification processes and ecological vulnerability beyond what conventional concentration-based pollution classifications can reveal.

In parallel, this work critically examines methodological evolution in PAH research, tracing the shift from single-matrix concentration surveys to multi-compartment, mechanistic, and biomarker-based approaches that incorporate stable isotope tracing, air–sea fugacity modeling, experimental bioassays, and GIS-anchored ecological risk frameworks. By contrasting analytical, experimental, and modeling strategies across studies, the review identifies strengths, constraints, and standardization challenges, emphasizing how sublethal and chronic responses frequently emerge at concentrations far below regulatory thresholds. Ultimately, the review seeks to redefine how PAH risks are assessed in coral reefs, arguing for integrated monitoring frameworks that account for metabolic stress, trophic transfer, and atmospheric deposition, while also outlining key research priorities needed to support meaningful conservation and policy decisions.

MATERIAL AND METHOD

This review was developed through a systematic and comprehensive literature synthesis focusing on peer-reviewed publications addressing polycyclic aromatic hydrocarbons (PAHs) in coral reef ecosystems across global regions. Research articles were identified using scientific databases including Scopus, Web of Science, and ScienceDirect, employing keyword combinations such as “PAHs,” “coral reefs,” “bioaccumulation,” “air-water exchange,” “WAF/HEWAF toxicity,” and “trophic transfer(Lima *et al*., 2026 ;Zheng *et al*., 2026) Studies were included if they provided quantitative PAH data from environmental matrices (water, sediments, atmosphere, soils, particulate matter) or biological compartments (coral tissues, mucus, zooxanthellae, benthic invertebrates, and reef fish), or if they presented experimental or modelling approaches relevant to PAH exposure or ecological effects. Both field and laboratory investigations published between 2017 and 2025 were prioritized to capture contemporary methodological and conceptual advancements.

Data from each study were systematically extracted into comparative tables that categorized sampling designs, analytical approaches, concentration ranges, organismal responses, and identified sources. Comparisons were conducted across spatial gradients, ecosystem types, pollutant profiles, and analytical instrumentation to identify thematic patterns and methodological evolution. Special emphasis was placed on studies that integrated multi-matrix sampling, toxicological bioassays, isotopic tracing, GIS-based ecological risk mapping, or air–sea exchange modelling. The final synthesis draws connections across datasets to evaluate PAH pathways, reservoir behavior, organismal vulnerability, and implications for monitoring frameworks. The aim of this methodological process was not only to summarize existing findings but to identify research gaps and emerging directions essential for advanced reef pollution assessment.

RESULTS AND DISCUSSION

The comparative dataset compiled from multiple global studies reveals a deeply troubling yet highly consistent pattern: polycyclic aromatic hydrocarbons (PAHs) are now omnipresent across coral reef ecosystems, spanning the Arabian Sea, South China Sea, Brazilian Atlantic, Persian Gulf, Gulf of Suez, and oceanic archipelagos previously marketed as "pristine." Although many measured concentrations technically fit within what outdated regulatory frameworks label as *low to moderate contamination*, the biological responses described in this literature expose that such numerical classifications are disturbingly misleading. When PAHs infiltrate coral tissues, symbiotic algae, sediments, and reef-associated organisms, they exert effects disproportionately severe compared to their concentration scale, demonstrating that ecological vulnerability is driven far more by organismal physiology and trophic accumulation than by simplistic environmental threshold values.

Vignesh *et al*., (2024) reported some of the highest particulate loads on record in Lakshadweep, reaching 6469.86 ng g^{-1}, despite dissolved water-phase values of only 2.77–250.47 ng L^{-1}. This dichotomy suggests that particulate binding and resuspension cycles in reef lagoons can act as hidden reservoirs invisible to routine surface water monitoring. Meanwhile, cyclone-driven dilution temporarily suppressed dissolved concentrations, reinforcing that extreme weather events may mask long-term contamination rather than resolve it. In contrast, Feng *et al*., (2021) demonstrated that offshore reef systems in the South China Sea receive significant PAH inputs via atmospheric deposition, with gas-phase concentrations up to 113.1 ng m^{-3}, meaning reefs are being rained on by combustion exhaust before contaminants even enter shipping or industrial waterways.

Bioaccumulation patterns form an even more unsettling narrative. Xiang *et al*., (2018) showed coral tissues accumulating 333.88–727.03 ng g^{-1}, far exceeding sediment burdens, and enriched in high-molecular-weight carcinogens such as BaP and BkF—compounds strongly associated with genotoxic outcomes. Ranjbar Jafarabadi *et al*., (2020) intensified this picture with the highest coral-associated PAH concentrations yet recorded, reaching 1127 ng g^{-1} in tissues and an astonishing 1421 ng g^{-1} in zooxanthellae. Such values demonstrate the role of lipid-rich symbionts as biochemical traps, converting PAHs into chronic internal exposures rather than temporary external contamination. These findings obliterate the outdated belief that corals are passive receptors; they are, instead, biochemical concentrators capable of magnifying contamination by orders of magnitude beyond environmental levels. The trophic transfer demonstrated by Han *et al*., (2022), showing tissue PAHs of 44–70 ng g^{-1} in reef fish and benthic invertebrates with TMF values approaching 8.4, confirms that tropical reef food webs actively biomagnify contaminants rather than dilute them. This offers a concerning precedent for human seafood safety and reef apex predators.

Experimental results sharpen the mechanistic understanding behind these concentrations. Nordborg *et al*., (2022) demonstrated that coral larvae show severe impairments at NEC ~34 µg TAH L^{-1}, with lethal thresholds near 52.6 µg TAH L^{-1} under heavy fuel oil exposure, underlining that early life stages are catastrophically sensitive. Müller *et al*., (2021) showed that Symbiodinium glynnii exposed to up to 2315 ng L^{-1} ΣPAHs assimilated fossil carbon directly into cellular biomass, evidenced by $\delta^{13}C$ shifts—a biochemical horror story on its own. Meanwhile, van den Hurk *et al*., (2020) demonstrated that biomarkers in lionfish respond aggressively at 25 µg L^{-1}, meaning that even comparatively low concentrations trigger detoxification pathways and oxidative stress. Their absence in field-sampled fish suggests either rapid dissipation post-event or surprisingly low exposure levels despite hurricane-induced boat fuel dumping, illustrating how time-dependence and hydrodynamic context must be integrated into monitoring.

Spatial context further reinforces that PAHs do not conform to conventional geographic assumptions. The highest sediment concentration across all reviewed studies (3205.89 ng g^{-1}) occurred not in an industrial estuary but in an iconic ecotourism destination such as Fernando de Noronha (Mello *et al*., 2025). Similarly, Tan *et al*., (2022) reported 2.1–151 ng g^{-1} soil concentrations in remote reef islands, emphasizing that atmospheric fallout and long-range transport now equal the impacts once attributed solely to coastal industrialization. El-Alfy (2024) found much lower sediment values (23.9–66 ng g^{-1}) in the Gulf of Suez, yet the ecological risk ranking was high due to sediment characteristics and benthic exposure pathways, dismantling the simplistic assumption that concentration alone predicts ecological impact.

Briefly, this consolidated evidence reveals several overarching themes. First, PAHs in coral reefs operate as chronic, sublethal, multi-compartment pollutants rather than acute spill signatures. Second, coral reef species—from symbionts to fish—serve as bioaccumulative amplifiers that concentrate PAHs and transport them across trophic boundaries (Figure 1). Third, sediment loads and atmospheric pathways profoundly influence distribution, often decoupling exposure dynamics from direct point sources. Fourth, laboratory mechanistic trials consistently show that biological damage occurs at concentrations far below general regulatory thresholds. Finally, the illusion of ecological safety based on surface-water monitoring collapses when multi-matrix comparisons are applied.

In this context, PAHs may act as a chronic and often under-recognized stressor that contributes to coral reef degradation, particularly through sublethal effects that can exacerbate coral sensitivity to dominant drivers such as ocean warming and bleachingTheir ecological threat is not found in spectacular acute mortality, but in biochemical attrition—an invisible erosion of growth, recruitment, physiology, and interspecies energy transfer. If reef conservation intends to be more than ceremonial, PAH monitoring must expand beyond sediments and water into coral tissues, mucus, symbionts, and trophic networks, adopting biomarkers and isotopic tracing as standard diagnostic tools. Ignoring PAHs because their concentration columns look numerically small is a luxury coral reefs can no longer afford.

The bar chart in Figure 2. illustrates substantial variability in PAH concentrations across coral reef ecosystems and environmental matrices, reflecting both spatial heterogeneity and contrasting contamination pathways. Sediment and particulate fractions display the highest concentrations overall, particularly in industrially influenced regions such as Fernando de Noronha (Mello *et al*., 2025) and Lakshadweep particulate matter (Vignesh *et al*., 2024), where values reach the upper end of the dataset and indicate strong inputs from port activities, shipping, and coastal development. In contrast, dissolved water concentrations are generally lower, consistent with rapid dispersion and partitioning behavior of PAHs. However, the markedly elevated concentrations observed in biological compartments, especially zooxanthellae and coral tissues (e.g., Ranjbar Jafarabadi *et al*., 2020; Xiang *et al*., 2018), highlight strong bioaccumulation potential and point to biological matrices as sensitive indicators of chronic hydrocarbon exposure within reef systems.

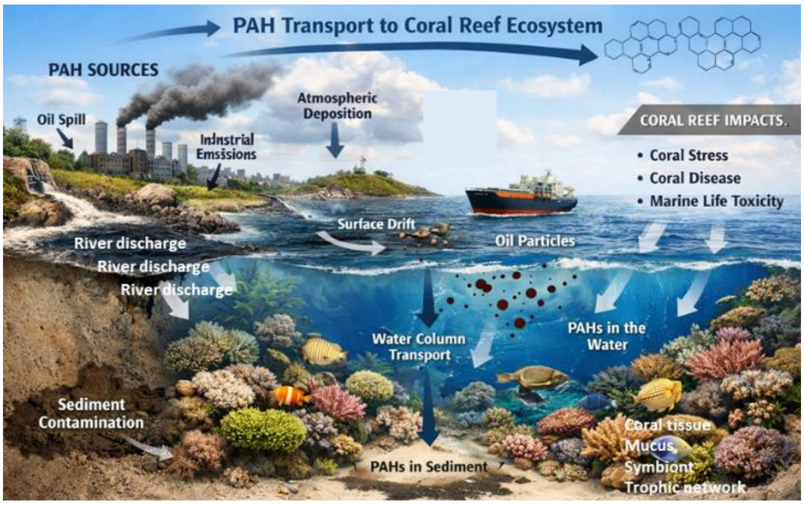

Figure 1. Transport pathways of polycyclic aromatic hydrocarbons (PAHs) from anthropogenic sources to coral reef ecosystems.

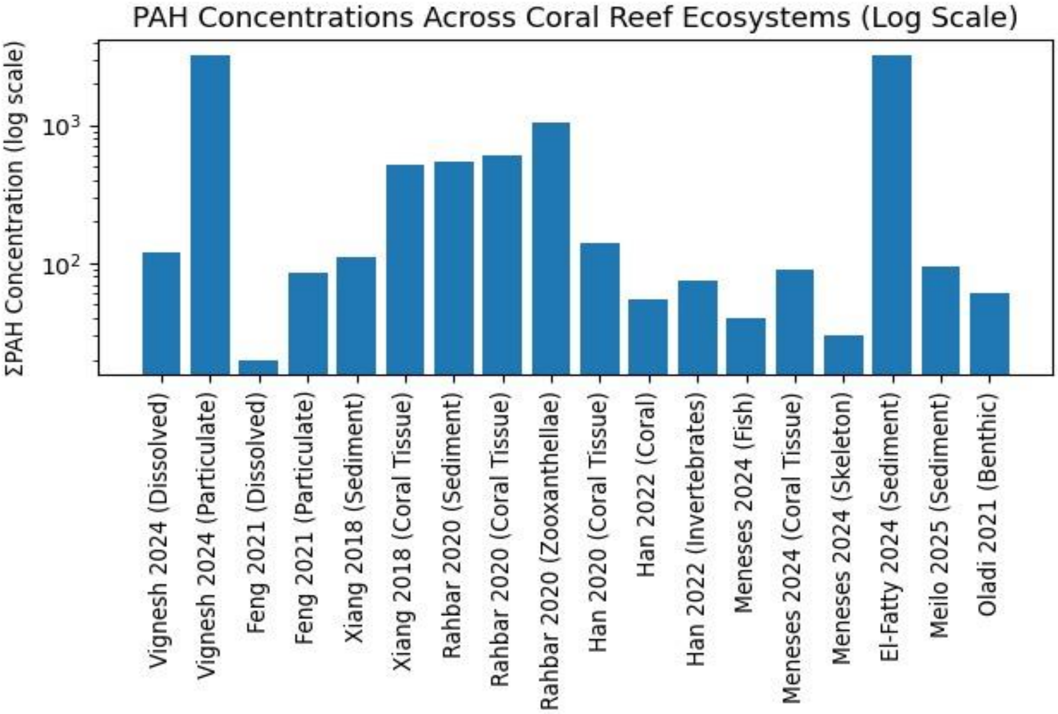

Figure 2. PAHs concentrations across coral ecosystems including water, sediments and organisms throughout the globe

The pattern of concentrations across trophic groups and substrates also underscores the important role of biological enrichment in mediating ecological risk. Coral tissues, mucus, and symbiotic microalgae consistently show higher PAH levels relative to adjacent sediments and bulk seawater, demonstrating effective uptake from both dissolved and particulate pathways. This supports previous findings on lipid-associated sequestration and trophic transfer, as further reinforced by biomagnification estimates reported by Han *et al*. (2022). The magnitude of variability across regions suggests that PAH contamination is not uniformly distributed but is strongly associated with local anthropogenic pressure, hydrodynamic processes, and matrix-specific retention capacity.. "Collectively, these results indicate that even concentrations traditionally categorized as low-to-moderate may represent ecologically significant exposures for corals, particularly under multi-stressor conditions where interactions with elevated temperature, UV radiation, and pathogenic or chemical stressors are often synergistic and bidirectional."

Although this review is explicitly focused on the tropical belt, the inclusion of data from extra-tropical regions is scientifically justified to provide a comparative framework that strengthens interpretation of PAH behavior in coral reef ecosystems. Coral-associated PAH dynamics are not governed solely by geographic boundaries but by interconnected physical, chemical, and atmospheric processes operating across latitudes, including long-range atmospheric transport, ocean circulation, and global petroleum-derived emissions (Feng *et al*., 2021; Tan *et al*., 2022). Incorporating non-tropical datasets enables the identification of baseline contrasts in PAH composition, sources (pyrogenic vs. petrogenic), and bioaccumulation patterns, thereby allowing clearer attribution of tropical-specific processes such as enhanced photodegradation, stronger stratification, and coral–symbiont interactions (Han *et al*., 2022; Menezes *et al*., 2024). Moreover, several studies have demonstrated that remote coral reef systems, including those in tropical regions, are influenced by transboundary pollutant fluxes originating outside their immediate geographic domain, particularly via atmospheric deposition and oceanic connectivity (Feng *et al*., 2021). Therefore, the inclusion of extra-tropical references is not a deviation from the scope, but rather a necessary methodological approach to contextualize tropical observations within a global continuum of PAH cycling, improve source apportionment, and avoid regionally biased interpretations of contamination levels and ecological risk

Methodological Advancements in PAH Research in Coral Reef Ecosystems

The collective body of research synthesized across the reviewed articles demonstrates a clear methodological evolution in the study of polycyclic aromatic hydrocarbons (PAHs) in coral reef environments (Table 1). Early approaches primarily quantified PAH concentrations in isolated environmental matrices, whereas contemporary studies apply increasingly integrated methodologies that combine chemical analyses, multi-compartment sampling, isotopic tracing, toxicological bioassays, and spatial modeling. This development reflects both technological progress in analytical chemistry and a conceptual shift toward understanding PAHs as dynamic components moving across environmental compartments and food webs, rather than static pollutants confined to sediments or surface waters.

Progression from Single-Matrix Chemical Monitoring to Multi-Compartment Sampling

Initial PAH studies in reef ecosystems typically emphasized sediment or seawater chemistry, focusing on spatial concentration patterns and basic diagnostic ratios. Examples include El-Alfy (2024) and early approaches in Xiang *et al*., (2018), who conducted single-season field campaigns focused on water and sediments. Their methodology relied heavily on solvent extraction techniques (e.g., Soxhlet extraction), silica-gel clean-up procedures, and gas chromatography–mass spectrometry (GC–MS), adhering to well-established pollutant quantification frameworks.

A significant methodological progression is evident in more recent studies such as Vignesh *et al*., (2024), Feng *et al*., (2021), Han *et al*., (2020; 2022), and Ranjbar Jafarabadi *et al*., (2020), which adopt multi-matrix strategies incorporating dissolved and particulate PAHs, sediments, coral tissues, coral mucus, zooxanthellae, and reef organisms. This broadened perspective enables characterization of environmental exposure pathways and bioaccumulation patterns. The methodological inclusion of atmospheric sampling by Feng *et al*., (2021) marks a conceptual shift by considering the atmosphere as a major PAH reservoir and vector to offshore reefs, enabled by gas–particle partitioning models and fugacity-based air–water flux calculations. Similarly, the use of contrasting environmental gradients, such as cyclone conditions in Vignesh *et al*., (2024) and industrial vs natural reef comparisons in Ranjbar Jafarabadi *et al*., (2020), has enhanced methodological resolution by embedding natural experiments within field campaigns.

Advances in Analytical Chemistry and Compound Scope

Across the reviewed literature, classical Soxhlet extraction remains a common foundation for sediment and biota analysis, but recent methodological improvements focus on efficiency and compound inclusivity. For example, Tan *et al*., (2022) implemented a QuEChERS-based workflow for soil extraction, increasing throughput and reducing solvent consumption. Meanwhile, Menezes *et al*., (2024) introduced microscale dispersive solid-phase extraction specifically optimized for coral tissue, enabling detailed analysis of novel compound classes such as Nitro- and Oxy-PAHs, which exhibit stronger mutagenic properties than parent PAHs. This expansion of analyte scope marks a critical methodological turning point: earlier studies focused exclusively on EPA-priority parent PAHs, while newer work recognizes the ecological importance of alkylated and derivative PAHs resulting from weathering, photolysis, and combustion.

Multi-compound approaches employed by Qiu *et al*., (2024) further broaden the analytical frontier by integrating legacy PAHs with halogenated contaminants and emerging pollutants, highlighting the transition from chemical surveillance to multi-pollutant ecosystem assessment. These developments represent a meaningful shift away from binary pollution quantification toward chemically and biologically contextualized risk interpretation.

Integration of Biological Endpoints, Isotopic Tracing, and Biomonitoring

The reviewed studies illustrate rapid expansion beyond purely chemical measurements toward biologically relevant methodology. Han *et al*., (2022) introduced stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) to derive trophic magnification factors (TMFs), providing one of the first mechanistic quantifications of contaminant movement through tropical coral reef food webs. This methodology transforms PAH studies from passive concentration mapping into functional ecological assessment.

Similarly, Müller *et al*., (2021) employed $\delta^{13}C$ tracing to demonstrate assimilation of crude-oil carbon by Symbiodiniaceae, revealing physiological consequences of PAH exposure not measurable through concentration data alone. Müller's combined approach integrating multigenerational culturing, WAF toxicity gradients, and isotopic fingerprinting represents a methodological breakthrough pointing toward molecular-level process inference.

In toxicology, Nordborg *et al*., (2022) developed chronic bioassays emphasizing sublethal endpoints including symbiont acquisition, photosystem efficiency, and growth suppression under UV-enhanced exposure scenarios. This methodological perspective corrects past overreliance on LC_{50} mortality data by showing that biologically meaningful damage occurs at pollutant levels far below thresholds typically classified as toxic.

In biomonitoring, van den Hurk *et al*., (2020) introduced bile fluorescence and CYP1A (EROD) enzyme assays, establishing a functional biomarker framework capable of quantifying metabolic response to PAHs in field-collected organisms. The use of lionfish as a high-trophic monitoring species represents a strategic innovation linking contaminant exposure to physiological response in mobile predator species.

Spatial Modeling and Integrated Environmental Risk Assessment

Recent advances in marine pollution research increasingly emphasize the integration of geospatial modeling with chemical datasets as a necessary step to translate contaminant measurements into ecologically interpretable and management-relevant information. Traditional reporting of PAH concentrations as isolated point data, while analytically robust, often fails to capture the spatial heterogeneity of contamination or its interaction with coastal geomorphology, habitat sensitivity, and human pressure gradients. In response, recent studies have adopted GIS-based frameworks that embed chemical measurements within spatially explicit vulnerability assessments, allowing contamination patterns to be evaluated in a broader ecological context.

El-Alfy (2024) pioneered the application of a GIS-driven Environmental Sensitivity Index (ESI) specifically tailored to PAH contamination in coastal systems (Table 1). This framework integrates sedimentary PAH concentrations with shoreline typology, hydrodynamic exposure, and ecological weighting factors to produce spatial vulnerability maps rather than simple concentration overlays. By combining chemical intensity with habitat sensitivity, the ESI approach highlights areas where moderate contaminant levels may pose disproportionate ecological risk due to low resilience or high biological value. Such spatially resolved risk assessments move beyond compliance-based thresholds and instead emphasize functional ecosystem vulnerability, providing a more realistic representation of contamination impacts in heterogeneous coastal environments.

Building on this foundation, Mello *et al*., (2025) expanded the ESI concept to incorporate multi-pollutant datasets and anthropogenic pressure proxies, including port proximity, shipping density, and industrial infrastructure. Their integrated model revealed discrete PAH hotspots exceeding 3000 ng g^{-1} within nominally protected oceanic Marine Protected Areas (MPAs), underscoring the disconnect between legal protection status and actual exposure risk. By coupling contaminant distributions with spatial indicators of human activity, the study demonstrated that MPAs are not chemically insulated systems, but rather embedded within broader seascapes shaped by maritime traffic, fuel handling, and coastal development.

Eventually, these geospatial-chemical frameworks represent a critical methodological shift in marine pollution science. Rather than treating contaminants as static chemical burdens, GIS-integrated models frame pollution as a spatially dynamic stressor interacting with ecological structure and management boundaries. This approach enhances the interpretability of chemical data for policymakers and conservation planners, enabling prioritization of monitoring, remediation, and enforcement efforts based on both contamination intensity and ecosystem sensitivity. Ultimately, the integration of spatial modeling with chemical analysis strengthens the linkage between environmental chemistry, ecological risk, and practical conservation decision-making, particularly in complex coastal and reef-associated systems.

Remaining Limitations and Future Methodological Needs

Across the studies, persistent limitations include weak temporal resolution, limited integration of hydrodynamic or atmospheric transport modeling, and absence of standardized WAF/HEWAF preparation protocols. Most field studies represent single-event or single-season sampling, leaving pollutant recovery dynamics unresolved. Alkylated PAHs, derivative compounds, and genomic markers of physiological stress remain insufficiently represented despite growing recognition of their importance. Future work should systematically integrate coral physiology (bleaching metrics, microbiome composition, immune response proteins) with multi-season, multi-pollutant monitoring, advancing methodology from documentation to prediction.

Oceanographic Drivers of PAH Distribution in Coral Reef Ecosystems

Polycyclic aromatic hydrocarbons do not magically arrange themselves into precise concentration gradients across coral reef ecosystems; they are sculpted by the physical and biogeochemical machinery of the ocean. "Hydrodynamic and biogeochemical processes play a critical role in regulating the environmental fate of PAHs. For example, microbial degradation pathways influence PAH persistence and transformation (Duran and Cravo-Laureau, 2016), while hydrodynamic forcing such as currents and sediment resuspension controls their distribution and partitioning between dissolved and particulate phases (Liu et al., 2018). In addition, stratification and air–sea exchange processes regulate vertical transport and atmospheric inputs of PAHs in coastal systems (Koudryashova et al., 2019)."The distribution of PAHs is therefore not primarily controlled by emission intensity alone, but by the oceanographic conveyor belts that move, accumulate, or re-release them from different environmental compartments (Dolphin et al., 1995; Guo et al., 2025). Coral reefs sit at the interface of these forces, making them both sinks and reactors in which PAHs undergo transformation and biological concentration.

Hydrodynamic circulation provides the foundational framework shaping PAH fate at the reef scale. Coral reefs positioned near boundary currents or strong tidal jets typically experience enhanced flushing, reducing dissolved-phase residence time and diluting concentrations in water columns. Unfortunately, this does nothing to prevent particulate-associated PAHs from accumulating within reef-lagoon sediments, where repeated resuspension events can bypass dilution and sustain biological exposure long after initial pollution pulses have passed. In contrast, semi-enclosed reef lagoons, such as those of the Lakshadweep Archipelago, reveal dramatically different dynamics. Weak circulation combined with low tidal amplitude creates stagnation zones in which suspended particulate matter becomes a long-term PAH reservoir. The extreme values reported by Vignesh et al., (2024), reaching 6469.86 ng g^{-1} in particulate fractions, exemplify how hydrodynamic confinement transforms transient atmospheric or coastal emissions into chronic contamination problems for benthic communities. In these environments, the partition coefficient (Kd) governing dissolved-to-particulate exchange becomes a decisive predictor of accumulation, particularly for higher molecular–weight PAHs that preferentially associate with organic-rich particulates.

Stratification and thermocline structure further modify PAH fate. Thermal and haline stratification limit vertical mixing, trapping dissolved PAHs within surface layers. During marine heatwaves and monsoonal calm periods, strong surface stratification can intensify, creating a physical barrier that prevents vertical redistribution and locking contaminants into the photic zone, where corals, plankton, and reef fishes conduct nearly all metabolic processes. Conversely, deep mixing events driven by internal waves or seasonal overturning can suddenly redistribute buried PAHs from thermocline interfaces into reef environments, producing short-lived but biologically intense pulses of exposure. Such pulses produce what field researchers misidentify as declining contamination trends when surface concentrations drop, only for pollution to rebound once hydrodynamic forcing shifts again. In other words, stratification selectively hides contamination from standard monitoring methods that focus on surface water rather than depth-resolved sampling.

Atmospheric deposition is now recognized as one of the most powerful long-range drivers controlling PAH delivery to reefs far from industrialized coasts. Offshore South China Sea reefs sampled by Feng *et al.*, (2021) showed gas-phase PAHs up to 113.1 ng m^{-3}, indicating that

Table 1. Integrated Summary of PAH Concentrations and Analytical Methods Across Global Coral Reef Studies

Study	Region / Site	Matrix	PAH Concentration Range	Extraction and Cleanup	Instrumentation	Key Methodological Notes
Vignesh *et al*., 2024	Lakshadweep Archipelago (Arabian Sea)	Dissolved	2.77–250.47 ng L^{-1}	GF/F filtration + liquid–liquid extraction (DCM)	GC–MS (SIM)	Partitioning (Kd), cyclone-driven variability
		Particulate (SPM)	0.44–6469.86 ng g^{-1}	Soxhlet (DCM/MeOH) + silica–alumina cleanup		Strong dissolved–particulate coupling
Feng *et al*., 2021	South China Sea	Water (dissolved)	1.94–22.6 ng L^{-1}	SPE (C18) after filtration	GC–MS/MS (triple quadrupole)	Air–water flux modeling
		Gas phase air	18.0–113.1 ng m^{-3}	PUF sampling + Soxhlet		Atmospheric deposition dominant
		Particle phase air	0.2–3.7 ng m^{-3}	Quartz filter + cleanup		Monsoon-driven distribution
Xiang *et al*., 2018	Sanya, South China Sea	Sediment	67.29–196.99 ng g^{-1}	Freeze-dry + MSPD + multilayer cleanup	GC–MS (SIM)	Multi-matrix comparison
		Coral tissue	333.88–727.03 ng g^{-1}	Same as above		Strong bioaccumulation
Ranjbar-Jafarabadi *et al*., 2020	Persian Gulf	Sediment	220–578 ng g^{-1}	Soxhlet + silica chromatography	GC–MS (SIM)	Perylene source apportionment
		Coral tissue	47–1127 ng g^{-1}	Same		Lipid-driven accumulation
		Zooxanthellae	679–1421 ng g^{-1}	Same		Highest accumulation compartment
Han *et al*., 2020	South China Sea	Coral tissue & mucus	Tens–hundreds ng g^{-1}	Organic solvent extraction (Soxhlet/ASE)	GC–MS	Mucus as PAH hotspot
Han *et al*., 2022	South China Sea	Coral	~70.5 ng g^{-1}	Classical solvent extraction	GC–MS/MS + IRMS	TMF = 2–8.4 (biomagnification)
		Invertebrates / Fish	~44–50 ng g^{-1}			Food web transfer
Nordborg *et al*., 2022	Laboratory	Coral larvae	NEC ~34 µg L^{-1}; LC$_{50}$ 52.6 µg L^{-1}	WAF/HEWAF preparation	GC–MS / HPLC	Toxicity thresholds, phototoxicity
Cao *et al*., 2025	South China Sea	Coral Symbiodiniaceae	Up to 56.05 µg g^{-1}	Optimized co-extraction (PAHs + antibiotics)	GC–MS/MS + LC–MS/MS	Co-toxicity effects
Menezes *et al*., 2024	Brazil (S. Atlantic)	Coral tissue	23–138 ng g^{-1}	Microscale dispersive SPE	GC–MS/MS	Nitro- & Oxy-PAHs detected
		Skeleton	~7 ng g^{-1}	Separate processing		Weak archive vs tissue
Müller *et al*., 2021	Laboratory (oil spill)	Symbiodinium	0–2315 ng L^{-1}	WAF extraction	GC–MS + IRMS	δ^{13}C confirms oil assimilation
van den Hurk *et al*., 2020	Florida Keys	Water (HEWAF)	24.7–2728 µg L^{-1}	HEWAF prep + extraction	GC–MS + biomarkers	Biomonitoring via fish
Tan *et al*., 2022	Xisha Islands	Soil	2.1–151 ng g^{-1}	QuEChERS extraction	GC–MS/MS	Soil as secondary PAH source
El-Alfy, 2024	Gulf of Suez / Mediterranean	Sediment	23.9–66 ng g^{-1}	Soxhlet + silica cleanup	GC–MS	GIS-based risk mapping
Mello *et al*., 2025	Fernando de Noronha	Sediment	up to 3205.89 ng g^{-1}	Multi-analyte extraction	GC–MS/MS	Hotspots near port areas
Oladi & Shokri, 2021	Persian Gulf	Benthic organisms	38.5–125 ng g^{-1}	Sequential ASE extraction	GC–MS	Multi-indicator reef health

long-range atmospheric transport can surpass direct marine discharge in magnitude. Monsoon-driven air mass transport redistributes combustion-derived aerosols across ocean basins, carrying pyrogenic PAHs produced from urban traffic, biomass burning, and industrial chimneys thousands of kilometers from their source. Seasonal reversal of monsoonal winds in the northern Indian Ocean alters deposition patterns, turning regions previously seen as remote refuges into seasonal sinks of atmospheric pollutants. Dry deposition concentrates coarse-bound PAHs onto sea surfaces, while wet deposition during monsoon rains forcefully delivers PAHs into lagoon hydrology, creating rapid contamination spikes. Coral mucus, positioned at the water–air–organism interface, absorbs these compounds efficiently, explaining why coral mucus often contains higher PAH burdens than surrounding tissue.

Wave climate and storm regimes produce an additional control on spatial redistribution. Cyclones, typhoons, and storm surges enhance sediment resuspension and remobilize buried PAHs into the water column, forcing repeated exposure cycles that can last months after initial contamination. Vignesh *et al*., (2024) documented cyclone-driven dilution of dissolved PAHs that temporarily masked chronic contamination status, illustrating the risk of misinterpretation when sampling coincides with post-storm flushing. The same turbulence that clears surface water can simultaneously re-expose reef benthos through sediment plume redistribution. Corals, seagrass beds, and filter feeders, positioned directly in the sediment resuspension pathways, are subjected to particulate-associated PAHs that may be biologically more potent due to their hydrophobic affinity and binding preference for lipids and organic matrices.

Upwelling and mesoscale eddies exert another level of complexity (Figure 3). Upwelling zones bring deep, cooler waters rich in nutrients and particulate organic matter to the surface. While celebrated for enhancing fisheries productivity, these features also supply PAH-laden sediments and dissolved contaminants from depth (Ya *et al*., 2017; Liu *et al*., 2021; Shi *et al*., 2024). Coral assemblages positioned close to upwelling margins risk constant exposure to recycled contaminants regardless of atmospheric or terrestrial inputs. The eddy–front interactions in the western boundary current systems act as massive stirring mechanisms capable of transporting PAHs across basin scales. Such eddies can concentrate contaminants along frontal zones, forming biological “hotspots” where corals and reef fish are repeatedly dosed with recirculating contaminants rather than episodic pulses (Ko *et al*., 2014; Ranjbar Jafarabadi *et al*., 2018; Liu *et al*., 2020).

Sediment composition mediates contaminant release dynamics at the seafloor. Carbonate reef sediments differ markedly from siliciclastic sediments typical of estuaries and industrial coasts. Low organic matter content and coarse grain fractions reduce adsorption capacity, implying that carbonate sediments should theoretically hold fewer PAHs (Armynot du Châtelet *et al*., 2009; Guerra *et al*., 2009; Marini and Annibaldi, 2022). Yet empirical data reveal the opposite: carbonate reef frameworks often exhibit disproportionate biological accumulation relative to sediment loads. This is attributable not to sediment storage capacity but to sediment turnover. Fine organic-rich particles settle into microdepressions in complex reef topography and are later resuspended by wave and tidal forcing, creating recurring pulses of particulate-bound PAHs to coral feeding surfaces. Reef crests amplify hydrodynamic shear, churning sediments and resurfacing contaminants—an overlooked mechanism that decouples sediment mass concentration from biological exposure (Bainbridge *et al*., 2014; Ko *et al*., 2014; Brodie, 2016).

Biogeochemical redox gradients at the sediment–water interface contribute to the release and transformation of PAHs. Hypoxic sediment conditions promote chemical reduction pathways that alter PAH solubility, producing derivative forms (Nitro-PAHs, Oxy-PAHs) with greater mutagenic and genotoxic potential (Nzila, 2018; Chen *et al*., 2023b). Strong temperature anomalies intensify this behavior by modifying bacterial degradation rates and oxygen consumption. Such feedback mechanisms explain why PAH toxicity under warming and acidification is elevated despite constant environmental concentrations. Ocean warming accelerates contaminant metabolism in organisms and enhances membrane permeability, while acidification changes PAH protonation and bioavailability. Combined stressors produce synergy rather than additivity, meaning that environmental thresholds derived from temperate experimental systems are largely meaningless for tropical reef prediction (Sparagon *et al*., 2024; Ejileugha and Out 2025; Marinho da Luz 2025).

Ultimately, the spatial fingerprints of PAH contamination reflect the sum of these oceanographic drivers rather than the magnitude of input sources alone. Remote MPAs with minimal industrial exposure can become contamination hotspots due to atmospheric connectivity, sediment trapping geometry, and hydrodynamic stagnation. Meanwhile, heavily industrialized zones may appear cleaner due to enhanced flushing, only to host high biological burdens invisible to chemical monitoring. The Persian Gulf illustrates this paradox perfectly: moderate sediment PAH values coexist with extreme organismal concentrations because thermal stress, hypersalinity, and restricted circulation amplify biological vulnerability and magnify pollutant uptake (Perra *et al*., 2011; Hu *et al*., 2021; Ranjbar Jafarabadi *et al*., 2024).

The lesson, which humanity seems determined to ignore, is that coral reef PAH contamination is fundamentally an oceanographic problem masquerading as a pollution issue. Regulatory frameworks based solely on concentration benchmarks are scientifically indefensible, because the severity of impact depends on circulation, hydrodynamics, trophic positioning, and climate forcing far more than environmental load alone. Integrating PAH research with physical oceanography, biogeochemistry, remote sensing, and hydrodynamic modeling is no longer an academic luxury; it is a survival requirement for coral ecosystems already collapsing under multiple stressors (Pendleton *et al*., 2016; Uthicke *et al*., 2016; Bieg *et al*., 2024).

Coral reefs do not die from single shocks but from the cumulative attrition orchestrated by the invisible architecture of the ocean. Until monitoring, modeling, and management reflect this physical reality, PAHs will continue functioning as silent accelerants in the decline of coral reef resilience under rapidly evolving climate regimes (Li *et al.,*2021; Sun *et al*., 2022; Tignat-Perrier *et al*., 2022).

Implications for New Regulation and Management

The emerging picture of PAHs in coral reef ecosystems exposes a fundamental misalignment between existing regulatory frameworks and the actual modes of ecological injury observed in tropical reefs. Most contemporary sediment and water quality guidelines for PAHs are derived from temperate estuarine or riverine systems, emphasize bulk concentrations in one or two matrices, and rely on threshold values designed to prevent overt toxicity or mortality (Moreira *et al.*, 2022; Dorleon *et al*., 2025). In contrast, the evidence synthesized in this review shows that coral reefs experience (i) chronic, multi-matrix exposure, (ii) strong bioaccumulation and trophic magnification, and (iii) sublethal but functionally severe biological responses at concentrations that sit comfortably below many current guideline values (Negri *et al*., 2019). This discrepancy implies that regulatory benchmarks grounded solely in dissolved or sedimentary concentrations are no longer defensible as indicators of “safe” conditions for tropical coral reef (Gardon *et al*., 2025).

A key regulatory implication is the need to move beyond single-matrix, concentration-based criteria toward multi-matrix, organism-centered standards. Corals, Symbiodiniaceae, and reef-associated organisms repeatedly exhibit PAH burdens

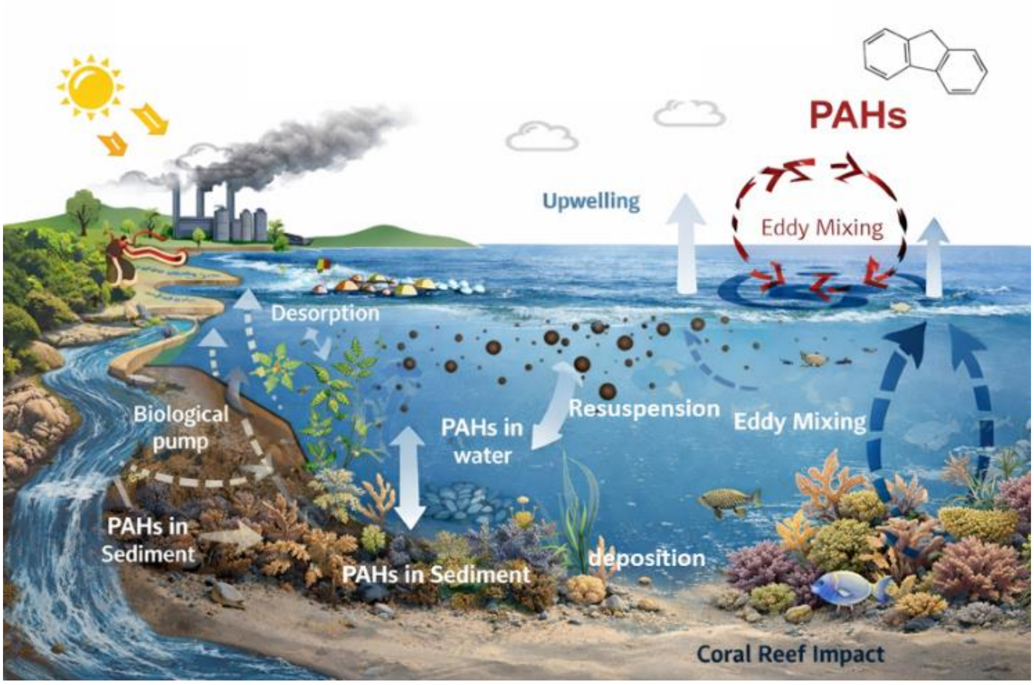

Figure 3. Upwelling and eddies roles to the PAH distribution in the water column.

one to two orders of magnitude higher than adjacent sediments or water, and selectively retain high-molecular-weight, carcinogenic, Nitro-, and Oxy-PAHs. Instead of evaluating risk only from dissolved ΣPAHs in water or dry-weight sediment values, regulatory frameworks should formally incorporate (Ashok, 2022; Han *et al*., 2022): (i) PAH concentrations in coral tissues, mucus, and symbionts as primary bioindicator endpoints (Ranjbar Jafarabadi *et al*., 2021; Cao *et al*., 2024); (ii) trophic magnification factors (TMFs) and biota–sediment accumulation factors (BSAFs) as indicators of food-web level risk (Li *et al*., 2021; Han *et al*., 2022) ; and (iii) biomarker responses (e.g. oxidative stress, detoxification enzymes, early-life stage impairment) as regulatory lines of evidence equivalent in weight to chemical thresholds (Xiang *et al*., 2019). This shift would align regulation with the biological reality that reefs are damaged long before water or sediment concentrations exceed generic guideline values.

Additionally, the strong role of oceanographic and atmospheric drivers in structuring PAH distribution demands that regulation and management explicitly embed physical context into assessment and zoning. The review highlights how semi-enclosed lagoons, stratified water columns, weakly flushed bays, and atmospheric deposition “shadows” convert relatively modest PAH inputs into chronic exposure regimes. Conversely, high-flow regions may show low dissolved concentrations yet still sustain high biological burdens due to rapid uptake and trophic transfer. This means that a uniform numerical threshold applied across all reef settings is inappropriate. Instead, risk-based management should classify reef areas into hydrodynamic and atmospheric exposure categories (e.g. lagoonal retention zones, upwelling margins, atmospheric deposition corridors, port-adjacent reefs) and apply differentiated monitoring intensity and precautionary limits. In high-retention or high-deposition settings, more conservative trigger values and stricter emission controls are warranted, given the higher probability of long-term PAH accumulation and remobilization.

An additional implication emerges for the design and management of marine protected areas (MPAs) and broader spatial planning frameworks. The detection of elevated PAH concentrations in sediments and biota within remote or offshore MPAs challenges the long-standing assumption that geographical isolation from coastlines inherently confers chemical protection. Evidence increasingly shows that offshore reef systems are exposed to PAH inputs through multiple non-terrestrial pathways, including long-range atmospheric deposition, routine vessel traffic, and port-related activities operating within or adjacent to MPA boundaries. As a result, spatial protection based solely on remoteness fails to safeguard reefs from hydrocarbon contamination (Ollivon *et al*., 2002; Li *et al*., 2021; Menezes *et al*., 2023).

Regulatory instruments therefore need to: (i) classify certain MPAs as “chemically vulnerable” based on shipping density, port proximity, atmospheric pathways, and lagoon geometry; (ii) incorporate PAH-specific performance indicators into MPA management plans (e.g. target maxima for coral tissue ΣPAHs, frequency of biomarker exceedances, or TMF thresholds); and (iii) regulate shipping lanes, anchorage zones, and bunkering operations in and around MPAs using strict PAH-oriented risk criteria, not just generic oil spill risk. For oceanic MPAs, this may include limiting certain fuel types, imposing speed or route constraints, and requiring on-board PAH monitoring or enhanced spill response readiness.

Moreover, spill preparedness and response protocols need substantial revision. Traditional oil spill response still prioritizes surface slicks, short-term dissolved concentrations, and shoreline impacts, with ecological success often judged by rapid return of dissolved hydrocarbons to near-baseline levels. The coral-focused literature demonstrates that this is a flawed benchmark: particulate associations, sediment trapping, and biological accumulation ensure that reefs remain chemically and biologically affected long after surface water appears “clean.” New regulations should require that spill risk assessment and response plans in coral reef regions: (i) include pre- and post-spill multi-matrix baselines (water, particulates, sediments, coral tissues, mucus, key invertebrates, and fish); (ii) monitor early-life stages (larvae, recruits) and symbionts using sensitive physiological and molecular endpoints; (iii) apply time-integrated sampling tools (e.g. passive samplers, biomonitor species) to capture pulsed and resuspended exposures; and (iv) maintain surveillance for derivative PAHs (Nitro/Oxy-PAHs) and chronic biomarker responses for months to years post-spill. Regulatory closure of a spill event should thus be contingent not only on water concentrations but on documented recovery of biological and trophic indicators.

Subsequently, the incorporation of PAHs into climate-resilience and coral restoration strategies is unavoidable. PAHs interact synergistically with thermal stress, ocean acidification, UV radiation, and disease, accelerating bleaching risk and reducing recovery potential. Reef restoration projects that transplant corals or engineer “climate-resilient” genotypes will be undermined if undertaken in chemically compromised settings. Management frameworks therefore should: (i) treat PAH status as a core criterion for site selection in active restoration and assisted evolution programs; (ii) integrate PAH monitoring into early-warning systems for mass bleaching or disease outbreaks, recognizing that chemically stressed corals have reduced physiological margin under heatwaves; and (iii) encourage the development and adoption of “pollution-resilient” indicators, combining thermal tolerance metrics with contaminant sensitivity profiles. At policy level, PAHs should be recognized as a key non-climatic driver that modulates the effectiveness of climate mitigation and adaptation interventions on reefs.

Then, the methodological advances summarized in this review suggest a clear direction for next-generation regulatory monitoring frameworks. Standard operating procedures should evolve to include: (i) Routine measurement of PAHs in coral tissues, mucus, and selected bioindicator species alongside sediment and water; (ii) Harmonized analytical suites that include parent, alkylated, Nitro-, and Oxy-PAHs, reflecting real toxicological mixtures; Use of stable isotopes and biomarker panels to detect early stress before visible degradation; (iii) Integration of GIS-based risk mapping, combining PAH levels, hydrodynamic exposure, ecosystem sensitivity, and human use to prioritize management action; (iv) Development of tiered trigger values, where crossing chemical thresholds automatically initiates biomarker and food-web level assessments rather than waiting for visible ecological decline.

Finally, these scientific insights have a broader governance implication: effective regulation of PAHs in coral reefs cannot be siloed within marine pollution control alone. Atmospheric emissions policies, fuel standards, port and shipping regulations, land-use planning, wastewater management, and climate policy all shape reef PAH exposure. A credible management response requires cross-sectoral integration, where reef-focused PAH limits feed back into decisions on coastal industrial siting, vessel routing, combustion controls, and regional air quality management. At regional scales, especially in semi-enclosed seas and archipelagic states, transboundary coordination is essential, as atmospheric and oceanographic connectivity easily bypasses national jurisdiction boundaries.

Across the tropical belt, the compiled evidence demonstrates that PAHs are now intrinsic components of coral reef chemical landscapes rather than sporadic contaminants. Concentration patterns across dissolved, particulate, sedimentary, and biological compartments show consistent enrichment in particulate and biotic reservoirs, with corals, Symbiodiniaceae, and reef-associated fauna functioning as efficient concentrators of both parent and derivative PAHs. These biological archives reveal selective retention of high-molecular-weight and carcinogenic congeners, as well as Nitro- and Oxy-PAHs, indicating in situ transformation and weathering processes that further increase toxicological relevance. The contrast between relatively modest dissolved concentrations and orders-of-magnitude higher burdens in particulate matter, tissues, and symbionts underscores the inadequacy of surface-water benchmarks as proxies for ecological risk.

Pathway analyses highlight that PAH loading in coral reefs is governed by interconnected atmospheric, hydrodynamic, and terrestrial processes rather than simple proximity to point sources. Atmospheric deposition to offshore reefs, lagoonal retention and resuspension, and soil- and sediment-mediated recycling collectively sustain chronic exposure regimes even in marine protected areas and nominally remote settings. Experimental work with coral larvae, Symbiodiniaceae, and reef fishes confirms that sublethal impairment, metabolic reallocation, and heritable fitness loss occur at concentrations below many existing guideline values, while trophic magnification factors demonstrate that PAHs can intensify along food webs rather than attenuate.

All in all, these findings reframe corals and their symbionts as integrated chemical archives that record both contamination history and biological response. Effective management of PAH risks in coral reefs will require monitoring frameworks that prioritize multi-matrix sampling, incorporate biomarkers and isotopic tracers, and explicitly consider co-stressors such as warming, UV radiation, and co-occurring pollutants. Regulatory approaches based solely on bulk water or sediment concentrations are likely to underestimate true ecosystem vulnerability. Integrating PAHs into reef conservation, spill preparedness, and climate-resilience planning is therefore essential to prevent further erosion of coral reef function in an increasingly hydrocarbon-enriched ocean.

CONCLUSION

Polycyclic aromatic hydrocarbons (PAHs) are now recognized as persistent stressors in coral reef environments rather than sporadic contaminants. Evidence across tropical regions shows strong compartmentalization, with higher concentrations in sediments, particulate matter, and coral-associated matrices (e.g., tissues, mucus, Symbiodiniaceae) than in the dissolved phase. The frequent detection of high-molecular-weight and transformed PAHs (e.g., Nitro- and Oxy-PAHs) further indicates that reefs function as active biogeochemical systems where transformation and biological retention enhance toxicological relevance. Spatial patterns of PAHs are shaped more by oceanographic and atmospheric processes than by simple proximity to sources. Mechanisms such as atmospheric deposition, lagoonal retention, resuspension, stratification, and mesoscale circulation can sustain chronic exposure even in remote reefs. Biological evidence consistently shows that sublethal effects, including metabolic disruption, immune suppression, and impaired reproduction, occur at concentrations often classified as low to moderate, highlighting limitations of conventional risk thresholds. Overall, PAH contamination in coral reefs should be understood as a multi-compartment, process-driven issue influenced by hydrodynamics, atmospheric inputs, and interacting stressors. Improved assessment requires integrated, multi-matrix monitoring combined with biological indicators to better capture ecological risk in tropical reef systems.

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