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Emerging Contaminants in Indonesia: Occurrence, Management Practices, and Regulatory Challenges - A Review

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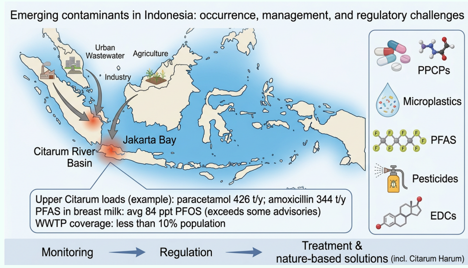
ABSTRACT



Emerging contaminants (ECs) including pharmaceuticals, microplastics, per- and polyfluoroalkyl substances (PFAS), modern pesticides, and endocrine-disrupting chemicals pose growing threats to Indonesian aquatic ecosystems and human health. This comprehensive review examines the occurrence, sources, environmental impacts, and management approaches for ECs across Indonesia's diverse aquatic environments. Analysis of published research reveals pervasive contamination in Indonesian surface waters, sediments, and biota, with particularly severe pollution documented in Java's industrialized river basins and coastal zones. The Citarum River Basin and Jakarta Bay exemplify critical hotspots where pharmaceutical loads reach hundreds of tons annually (426.1 tons paracetamol, 343.7 tons amoxicillin in Upper Citarum), microplastic abundances rank among the world's highest, and complex industrial chemical mixtures fundamentally alter ecosystem function. PFAS contamination in breast milk samples (average 84 ppt PFOS) exceeds international health advisory limits, while pesticide residues from intensive agriculture contaminate lakes and reservoirs. Indonesia's regulatory framework faces critical gaps, as Government Regulation No. 22 of 2021 addresses conventional pollutants but lacks specific standards for most ECs. Wastewater treatment infrastructure serves less than 10% of the population, with conventional technologies achieving incomplete EC removal. Monitoring capacity remains constrained by limited analytical infrastructure concentrated in Java, creating substantial geographic data gaps. Despite these challenges, opportunities exist through the Citarum Harum restoration program, growing research capacity, and context-appropriate technologies including nature-based treatment systems and locally-produced activated carbon. Priority interventions include phased regulatory development for well-documented substances, establishment of national monitoring programs with strategic geographic coverage, accelerated wastewater infrastructure deployment emphasizing decentralized solutions, targeted research on tropical-specific fate and effects, and strengthened governance through improved inter-agency coordination. This review provides the first comprehensive synthesis of EC contamination across Indonesia's archipelago, identifying critical knowledge gaps and actionable pathways for protecting aquatic biodiversity, safeguarding fisheries, and achieving sustainable development goals.

Keywords: *emerging contaminants; Indonesia; pharmaceuticals; microplastics; PFAS; PPCPs*

1. INTRODUCTION

Indonesia, as the world's fourth most populous nation and largest archipelagic country, has experienced unprecedented economic growth and rapid industrialization over the past three decades. This development trajectory, while contributing to improved living standards and economic prosperity, has simultaneously placed considerable pressure on the nation's aquatic ecosystems [1]. The expansion of industrial zones, urbanization of coastal areas, intensification of agricultural practices, and population growth have collectively resulted in increased discharge of various pollutants into rivers, lakes, and marine environments [2, 3]. Consequently, Indonesian water resources face mounting challenges from both conventional and emerging environmental contaminants, threatening the sustainability of aquatic ecosystems that millions depend upon for drinking water, food, and livelihoods.

Emerging contaminants, also known as contaminants of emerging concern (CECs), represent a diverse group of natural or synthetic chemicals that are not commonly monitored in the environment but have the potential to cause adverse ecological and human health effects [4, 5]. Unlike traditional pollutants such as nutrients and conventional organic matter, emerging contaminants encompass a wide array of substances including pharmaceuticals and personal care products (PPCPs), microplastics, per- and polyfluoroalkyl substances (PFAS), modern pesticides, endocrine-disrupting chemicals (EDCs), and various industrial chemicals [1, 6]. These compounds typically enter aquatic environments through multiple pathways: inadequately treated domestic and industrial wastewater, agricultural runoff, atmospheric deposition, and improper disposal of consumer products [7, 8]. What distinguishes emerging contaminants from conventional pollutants is not necessarily their novelty—many have been present in the environment for decades—but rather the growing recognition of their potential risks and the lack of comprehensive regulatory frameworks to address them [5].

The Indonesian context presents unique challenges and vulnerabilities regarding emerging contaminant pollution.

As a tropical archipelagic nation, Indonesia harbors extraordinary aquatic biodiversity and highly productive marine ecosystems that are potentially susceptible to chemical stressors [9, 10]. The country's limited wastewater treatment infrastructure compounds these concerns; current estimates suggest that less than 10% of domestic wastewater receives adequate treatment before discharge into water bodies [1, 3]. Furthermore, Indonesia's position as both a major manufacturing hub and agricultural producer means that diverse sources of emerging contaminants—from pharmaceutical production facilities and textile industries to intensive rice cultivation and aquaculture operations—are widely distributed across the archipelago [11, 12]. Climate factors typical of tropical regions, including high temperatures, intense solar radiation, and pronounced wet-dry seasonal patterns, may influence the fate, transport, and degradation pathways of emerging contaminants in ways that differ substantially from temperate environments where most research has been conducted [4]. These compounding factors underscore the urgent need to understand the occurrence, distribution, and impacts of emerging contaminants specifically within the Indonesian context.

Despite growing international attention to emerging contaminants, comprehensive assessments focused on Indonesia and Southeast Asia remain limited compared to research in developed nations [6, 4]. This review aims to address this knowledge gap by synthesizing available evidence on emerging contaminant pollution in Indonesian aquatic environments. Specifically, this review focuses on freshwater (rivers, lakes, and reservoirs), estuarine, and coastal marine environments, examining the major classes of emerging contaminants that have been detected and studied in Indonesia. The primary objectives of this review are to: (1) provide a comprehensive overview of the occurrence and concentrations of emerging contaminants documented in Indonesian waters; (2) identify major pollution sources and geographic hotspots where contamination is most severe; (3) evaluate the current regulatory framework and management practices for addressing emerging contaminant pollution; (4) assess treatment technologies and their effectiveness in the Indonesian context; (5) highlight critical knowledge gaps regarding ecotoxicological impacts, fate and transport processes in tropical environments, and long-term monitoring needs; and (6) recommend priority actions and research directions to strengthen Indonesia's capacity to manage emerging contaminants and protect aquatic ecosystem health.

This review is organized into six main sections following this introduction. Section 2 categorizes and characterizes the major classes of emerging contaminants detected in Indonesian waters, including PPCPs, microplastics, PFAS, pesticides, and EDCs, describing their sources, occurrence patterns, and concentrations. Section 3 identifies geographic hotspots and presents case studies from major river basins (including the heavily polluted Citarum River), coastal and marine environments (particularly Jakarta Bay), lakes and reservoirs (such as Lake Toba and Lake Rawapening), and industrial zones. Section 4 examines Indonesia's regulatory framework for water quality and emerging contaminants, assesses monitoring and analytical capabilities, reviews treatment technologies currently employed or under investigation, and discusses remediation initiatives including the high-profile Citarum Harum river cleanup program. Section 5 highlights critical knowledge gaps in long-term monitoring data, ecotoxicological research on tropical species, understanding of fate and transport processes under tropical conditions, and the need for cost-effective, locally-appropriate treatment solutions. Section 6 provides forward-looking perspectives and recommendations for strengthening regulatory frameworks, enhancing monitoring networks, investing in treatment infrastructure, building research capacity, and fostering regional cooperation within the ASEAN context. Finally, the review concludes by synthesizing key findings and outlining a path forward for comprehensive emerging contaminant management in Indonesia.

2. EMERGING CONTAMINANTS IN INDONESIA: CATEGORIES AND SOURCES

Emerging contaminants in Indonesian aquatic environments encompass a diverse array of chemical substances that have increasingly garnered scientific and regulatory attention due to their persistence, bioaccumulative potential, and toxicological significance. This section systematically categorizes the major classes of emerging contaminants that have been detected and studied in Indonesian waters, examining their sources, occurrence patterns, and concentrations (Table 1). Understanding the distribution and behavior of these contaminants is essential for developing effective management strategies tailored to Indonesia's unique environmental and socioeconomic context. Figure 1 provides a visual overview of the five major emerging contaminant categories, their representative compounds, primary sources, and key contamination statistics documented in Indonesian aquatic systems.

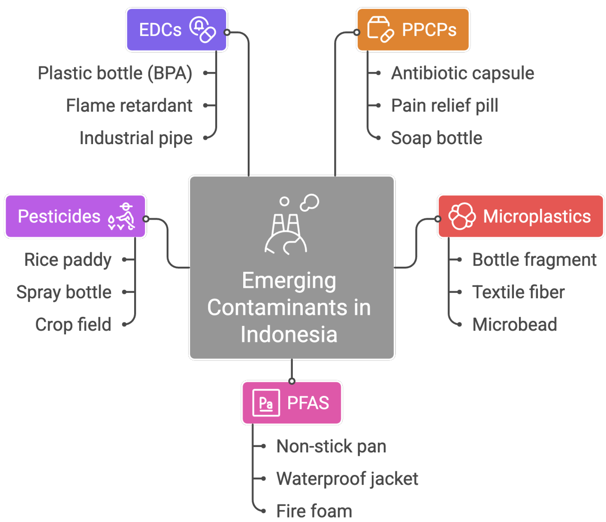


Figure 1. Overview of five major emerging contaminant categories in Indonesian aquatic environments: PPCPs, microplastics, PFAS, pesticides, and EDCs. The diagram shows representative compounds, primary sources, and key contamination statistics for each category.

2.1 Pharmaceuticals and Personal Care Products (PPCPs)

Pharmaceuticals and personal care products (PPCPs) constitute a particularly diverse and widespread class of emerging contaminants in Indonesian aquatic environments, reflecting the country's expanding healthcare infrastructure, growing pharmaceutical industry, and increasing consumer use of personal care formulations [13, 14]. PPCPs encompass a broad spectrum of biologically active compounds including prescription and over-the-counter medications, veterinary drugs, diagnostic agents, cosmetics, fragrances, and antimicrobial preservatives [15]. Unlike conventional industrial pollutants, PPCPs are specifically designed to be bioactive at low concentrations, often targeting biochemical pathways conserved across species, which raises concerns about their potential effects on non-target aquatic organisms even at trace environmental concentrations [16]. The persistence of many PPCPs through conventional wastewater treatment processes, combined with their continuous introduction into aquatic systems through daily human activities, results in pseudo-persistent contamination patterns where environmental concentrations remain relatively stable despite individual compound degradation [17].

Antibiotics represent one of the most extensively studied PPCP categories in Indonesian waters due to concerns about antimicrobial resistance development and ecotoxicological impacts on aquatic microbial communities [18, 13]. Commonly detected antibiotics in Indonesian aquatic environments include fluoroquinolones (ciprofloxacin, norfloxacin), sulfonamides (sulfamethoxazole, sulfadiazine), tetracyclines, macrolides (erythromycin, azithromycin), and beta-lactams (amoxicillin, ampicillin) [19, 14]. Hospital effluents serve as significant point sources of antibiotic contamination, with concentrations often orders of magnitude higher than those in receiving waters, reflecting intensive medical use and incomplete removal during on-site treatment where such facilities exist [20, 15]. Domestic wastewater also contributes substantial antibiotic loads, particularly in urban areas where self-medication practices are common and pharmaceutical waste disposal into sewage systems occurs frequently [13]. Aquaculture operations, particularly intensive fish and shrimp farming prevalent in Indonesian coastal areas, constitute another important source through prophylactic and therapeutic antibiotic applications, with sulfonamides and tetracyclines being among the most commonly used compounds in these settings [21, 22].

Analgesic and anti-inflammatory drugs form another prominent PPCP group detected in Indonesian waters [16]. Paracetamol (acetaminophen), ibuprofen, diclofenac, and naproxen are among the most frequently encountered analgesics, reflecting their widespread over-the-counter availability and high consumption rates in Indonesian society [17, 15]. Diclofenac, in particular, has garnered attention due to its known toxicity to vultures and potential impacts on aquatic organisms, even though environmental concentrations in Indonesia remain lower than those reported in some other developing nations [16]. These compounds enter aquatic environments primarily through domestic wastewater following human excretion of parent compounds and metabolites, with excretion rates varying from less than 10% to over 90% depending on the specific drug and individual metabolism [20].

Steroid hormones, both natural estrogens (estrone, estradiol, estriol) and synthetic compounds (ethinylestradiol from contraceptives), have been detected in Indonesian surface waters and wastewater, though at generally lower frequencies and concentrations compared to antibiotics and analgesics [23, 24]. These endocrine-active pharmaceuticals are of particular concern due to their ability to disrupt reproductive systems in aquatic organisms at extremely low concentrations (ng/L range), with documented feminization effects in fish populations observed in various countries [16]. The primary sources include domestic wastewater (from human excretion), hospital effluents, and potentially livestock operations, though comprehensive spatial surveys of hormone contamination in Indonesian waters remain limited [25].

Antimicrobial personal care ingredients, particularly triclosan and triclocarban, represent another PPCP category of environmental concern [17, 15]. These compounds, widely incorporated into soaps, toothpastes, and cosmetic products for their bactericidal properties, enter wastewater systems during showering and handwashing, subsequently persisting through conventional treatment and accumulating in receiving waters and sediments [15]. Triclosan exhibits toxicity to algae and aquatic invertebrates, and both compounds have been detected in Indonesian coastal waters and sediments, with concentrations generally correlating with population density and urbanization intensity [17].

The spatial distribution of PPCP contamination in Indonesia reflects urbanization patterns, healthcare facility locations, and aquaculture zones [13, 14]. Urban rivers and coastal waters receiving municipal wastewater discharges show the highest PPCP concentrations and diversity, with particular hotspots near major cities and hospital complexes [19, 26]. Studies have documented seasonal variations in PPCP occurrence, with some compounds showing elevated concentrations during dry seasons when reduced river flows result in lower dilution of wastewater inputs, while others peak during wet seasons due to mobilization from sediments or overflows from inadequate drainage systems [27]. The incomplete removal of PPCPs by conventional wastewater treatment plants—which were designed primarily for organic matter, nutrients, and pathogen removal rather than trace organic contaminant elimination—means that treated effluents continue to introduce these compounds into receiving waters [28, 29]. Table 3 summarizes concentrations and loads of selected PPCPs detected across various Indonesian aquatic environments, illustrating the widespread occurrence of these compounds in rivers, reservoirs, coastal waters, and aquaculture systems.

Health and ecological implications of PPCP contamination in Indonesian waters encompass multiple concerns [18, 30]. Environmental antibiotic residues may contribute to selection pressure favoring antimicrobial-resistant bacteria, potentially compromising future therapeutic effectiveness of these critical medicines [13]. Mixture effects, where multiple PPCPs co-occur and potentially interact synergistically or additively, remain poorly characterized in the Indonesian context despite being environmentally realistic scenarios [16]. Human health risks from PPCP exposure through drinking water consumption or fish consumption are generally considered low based on current detection levels, but data gaps regarding chronic low-dose exposure effects and potential endocrine disruption warrant precautionary approaches [25, 23]. Addressing PPCP contamination requires multifaceted strategies including source reduction through improved pharmaceutical stewardship and take-back programs, enhanced wastewater treatment incorporating advanced oxidation or adsorption processes capable of removing trace organics, and expanded environmental monitoring to better characterize the extent and trends of PPCP pollution across Indonesia's diverse aquatic environments [15, 29].

2.2 Microplastics

Microplastics—plastic particles smaller than 5 mm in size—have emerged as one of the most ubiquitous and visible forms of emerging contaminants in Indonesian aquatic environments, reflecting the nation's rapidly increasing plastic production and consumption alongside inadequate waste management infrastructure [5, 6]. Indonesia ranks among the world's top contributors to marine plastic pollution, with an estimated 0.48–1.29 million metric tons of plastic waste entering the ocean annually from inadequately managed terrestrial sources [4]. These microplastics originate from diverse sources including fragmentation of larger plastic debris (secondary microplastics), direct release of industrial plastic pellets and powders, degradation of synthetic textiles releasing microfibers during washing, tire wear particles, and intentional addition of microbeads in cosmetic and personal care products—though the latter source has diminished following regulatory restrictions in several countries [31, 8].

The occurrence of microplastics in Indonesian waters has been documented across multiple environmental compartments including rivers, estuaries, coastal seas, sediments, and biota [9, 10]. Rivers serve as major conduits transporting land-based plastic waste to marine environments, with microplastic concentrations in Indonesian rivers varying considerably based on upstream urbanization, industrial activities, and proximity to waste disposal sites [1, 3]. The Citarum River in West Java, one of the world's most polluted rivers, exhibits particularly high microplastic loads reflecting the intensive industrial and domestic activities in its watershed [2]. Coastal waters around major urban centers including Jakarta, Surabaya, Makassar, and Denpasar show elevated microplastic concentrations, with particle abundance often correlating with population density, tourism intensity, and proximity to river mouths [13, 14, 32]. The Ciliwung Estuary in Jakarta has been shown to contain microplastics that are subsequently ingested by resident fish species, demonstrating direct food web contamination pathways [33]. Mangrove sediments, which serve as critical nursery habitats for marine organisms, also accumulate substantial microplastic burdens, as documented in the Muara Angke Wildlife Reserve [34].

Microplastic contamination of Indonesian seafood and marine organisms has received increasing research attention due to implications for food safety and ecosystem health [2, 7]. Studies have documented microplastic ingestion across a wide range of marine taxa including commercially important fish species, shellfish (particularly mussels, oysters, and clams), crustaceans (shrimp and crabs), and even marine megafauna such as sea turtles and manta rays [9, 10]. The ingestion of microplastics by filter-feeding and detritivorous organisms appears particularly prevalent, as their feeding strategies do not discriminate between food particles and plastic fragments of similar size [3]. While current evidence suggests that the majority of microplastics ingested by fish remain in the gastrointestinal tract rather than translocating to muscle tissue consumed by humans, concerns persist regarding potential chemical transfer of plastic-associated contaminants (including additives such as phthalates and flame retardants, as well as persistent organic pollutants that sorb to plastic surfaces) and physical impacts on organism health [8].

The diversity of microplastic types detected in Indonesian waters reflects the varied sources and plastic production patterns [5]. Polyethylene (PE) and polypropylene (PP), the most widely produced thermoplastics used in packaging, bottles, and containers, constitute the dominant polymer types detected in Indonesian marine samples, followed by polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [6, 4]. Microfibers—elongated particles derived from synthetic textiles and fishing gear—represent a significant fraction of microplastic pollution in Indonesian coastal waters, highlighting the contribution of domestic laundry wastewater (containing fibers shed from polyester, nylon, and acrylic clothing) and fishing activities (involving degradation of nets and ropes) to this contamination [13]. Fragment morphology, resulting from breakdown of larger debris, predominates in many sampling locations, while pellets (pre-production plastic resin) appear near industrial zones and ports where plastic manufacturing or transport occurs [1]. Table 2 summarizes microplastic occurrence data from selected studies across various Indonesian aquatic environments, illustrating the diversity of contamination patterns, polymer types, and morphologies detected in different environmental matrices.

Seasonal and spatial variability in microplastic distribution patterns reflects complex interactions among sources, hydrodynamics, and environmental factors [2]. Monsoon patterns strongly influence microplastic transport, with increased riverine discharge during wet seasons mobilizing accumulated terrestrial plastic waste and transporting it to coastal and marine environments [3]. Hydrodynamic modeling studies in Indonesian coastal waters have demonstrated complex particle trajectories influenced by tidal currents, wind patterns, and river discharge, helping to identify accumulation zones and transport pathways [46]. Beach environments subject to tourism pressure show elevated microplastic concentrations, particularly following holiday periods and weekends when visitor numbers peak and waste generation increases [14]. Sediments act as important sinks for microplastics, with higher-density polymers and biofouled particles showing greater tendency to settle and accumulate in benthic environments where they may persist for extended periods and provide long-term exposure to sediment-dwelling organisms [7]. The capacity of microplastics to adsorb heavy metals such as lead and copper from the aquatic environment has been demonstrated in Indonesian waters, potentially enhancing toxicity through combined exposure to both plastic particles and sorbed contaminants [47].

The ecological implications of microplastic contamination in Indonesian waters encompass multiple pathways of potential harm [9, 10]. Physical effects include ingestion-related impacts such as gut blockage, reduced feeding, and false satiation, which have been demonstrated in various marine organisms though field evidence of population-level consequences remains limited [5]. Chemical effects may arise from leaching of plastic additives (plasticizers, stabilizers, flame retardants, colorants) or transfer of sorbed persistent organic pollutants and metals from ingested microplastics to organism tissues, though the magnitude of this exposure pathway relative to other contamination routes (direct uptake from water, consumption of contaminated prey) remains debated [4]. The potential for microplastics to serve as vectors for pathogenic microorganisms or invasive species, providing transport mechanisms across oceanic distances, represents another ecological concern warranting investigation in the Indonesian archipelagic context [8].

From a human health perspective, microplastic exposure pathways include consumption of contaminated seafood, drinking water (with microplastics detected in both tap water and bottled water globally), and inhalation of airborne particles [6, 31]. Current toxicological understanding suggests that larger microplastics (>10 μm) are poorly absorbed from the gastrointestinal tract and thus pose limited direct toxicity risk, though nanoplastics (<1 μm) may exhibit different behavior including potential for cellular uptake and translocation [5].

Table 1. Summary of major emerging contaminant categories detected in Indonesian aquatic environments.

Contaminant Category	Major Compounds Detected	Primary Sources	Key Detection Locations
PPCPs	Paracetamol, amoxicillin, ciprofloxacin, sulfamethoxazole, trimethoprim, oxytetracycline, caffeine, triclosan, triclocarban	Hospital effluent, domestic wastewater, aquaculture, pharmaceutical industry	Upper Citarum River Basin, Cirata Reservoir, Jakarta Bay, Surabaya River, Central Java coastal areas
Microplastics	PE, PP, PS, PET, PVC (fragments, fibers, pellets; 20–500 μm)	Urban runoff, industrial discharge, fishing activities, textile degradation, waste mismanagement	Jakarta Bay estuaries, Citarum River, coastal waters (Jakarta, Surabaya, Makassar, Denpasar), seafood/fish
PFAS	PFOS, PFOA, PFHxS, PFNA, PFHpA	Textile/leather manufacturing, food packaging, firefighting foams, consumer products	Jakarta Bay sediments, breast milk (Jakarta, Purwakarta), consumer products (clothing, packaging)
Pesticides	Organophosphates (profenofos, chlorpyrifos), pyrethroids (deltamethrin), carbamates (carbofuran), herbicides (glyphosate, paraquat), neonicotinoids	Rice paddies, vegetable farms, oil palm plantations, agricultural runoff	Rawa Pening Lake, paddy water, river water, lake water, agricultural watersheds
EDCs	Phthalates (DEHP, DBP, DEP, DMP), bisphenol A, nonylphenol, octylphenol, PBDEs, TBT	Plastics manufacturing, textile processing, antifouling paints, industrial discharge	Jakarta rivers and bay, harbors, ports, coastal sediments

Notes: PPCPs = pharmaceuticals and personal care products; PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; PVC = polyvinyl chloride; PFAS = per- and polyfluoroalkyl substances; PFOS = perfluorooctanesulfonic acid; PFOA = perfluorooctanoic acid; PFHxS = perfluorohexane sulfonic acid; EDCs = endocrine disrupting chemicals; DEHP = di(2-ethylhexyl) phthalate; DBP = di-n-butyl phthalate; DEP = diethyl phthalate; DMP = dimethyl phthalate; PBDEs = polybrominated diphenyl ethers; TBT = tributyltin.

Greater concern centers on chemical exposures from plastic-associated contaminants, particularly for populations with high seafood consumption rates such as many Indonesian coastal communities [7]. However, comprehensive human health risk assessments specific to Indonesian exposure scenarios remain lacking, and recommended tolerable intake levels for microplastics have not been established [8].

Addressing microplastic pollution in Indonesia requires integrated strategies spanning multiple scales and sectors [1, 3]. Source reduction through improved waste management infrastructure—including expansion of waste collection services to underserved areas, development of recycling and circular economy approaches, and reduction of single-use plastic consumption—represents the most effective long-term solution [13]. Wastewater treatment plants incorporating appropriate filtration can remove microplastics from domestic effluents before discharge, though implementation costs and technical requirements must be weighed against other water quality priorities [2]. Public awareness campaigns highlighting the environmental consequences of plastic pollution, combined with regulatory measures restricting problematic single-use items and establishing extended producer responsibility schemes, can help shift consumption patterns and production practices [4]. Enhanced monitoring programs to characterize microplastic abundance, distribution, and trends across Indonesian waters, employing standardized sampling and analytical protocols to ensure data comparability, are essential for assessing the effectiveness of management interventions and identifying priority areas for action [9, 6]. International and regional cooperation, including participation in ASEAN initiatives addressing marine plastic pollution and implementation of global agreements such as the emerging UN Plastics Treaty, will be critical for tackling this transboundary challenge that affects Indonesia's marine resources and coastal communities [5, 8].

2.3 Per- and Polyfluoroalkyl Substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) represent a family of synthetic organofluorine compounds characterized by strong carbon-fluorine bonds that confer exceptional chemical stability and resistance to environmental degradation [5, 6]. Comprising over 4,700 individual chemicals, PFAS have been extensively used since the 1940s in diverse industrial applications and consumer products due to their unique properties including water and oil repellency, thermal stability, and surfactant characteristics [4]. These "forever chemicals"—a term reflecting their extraordinary environmental persistence—have emerged as contaminants of critical concern globally, with detection in drinking water sources, surface waters, groundwater, sediments, and biota across all

Table 2. Microplastic occurrence in Indonesian aquatic environments based on selected studies.

Location	Matrix/ Compartment	Abundance/ Concentration	Dominant Polymer Type	Dominant Morphology	Size Range	Reference
Jakarta Bay (9 estuaries: Dadap, Angke, etc.)	Surface water (estuaries)	Highest: Dadap River; Lowest: Angke River; Order: North Jakarta > Tangerang > Bekasi	Polyethylene (PE)	Fragments	300–500 μm	[35]
14 harbors across Indonesia	Biota (Anchovies, *Stolephorus* spp.)	Mamuju: 688±1.15 MPs/ind; Krui: 645±7.02 MPs/ind	Not specified	Fiber and film	50–500 μm (majority); 20–50 μm	[36]
Indonesian waters (multiple locations)	Biota (25 fish species)	Average: 5.93 MPs particles/fish species; 45% of fish ingested MPs	Not specified	Not specified	Not specified	[9]
Citarum River, West Java	River water	High microplastic loads (one of world's most polluted rivers)	Not specified	Not specified	Not specified	[2]
Coastal waters (Jakarta, Surabaya, Makassar, Denpasar)	Coastal surface water	Elevated concentrations correlating with population density and tourism	PE, PP, PS, PET, PVC	Fragments, fibers, pellets	Variable	[1]
ASEAN region (Indonesia contributes most)	Multiple compartments	Indonesia: highest contributor to marine plastic pollution in ASEAN	PE, PP	Fragments	Variable	[7]

Notes: MPs = microplastics; ind = individual; PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; PVC = polyvinyl chloride. Data compiled from abstracts of cited references. "Not specified" indicates data not available in the abstract.

continents [31, 8].

In the Indonesian context, systematic studies on PFAS contamination in environmental waters remain limited compared to other emerging contaminant classes, though available evidence suggests widespread occurrence [39, 40]. The primary PFAS compounds of concern include perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), and their precursors, all of which have been detected in various Indonesian environmental matrices (Table 4) [39]. Historical data from 2004 revealed the presence of PFOS and PFOA in sediment samples collected from Jakarta Bay, with PFOS detected in all samples and PFOA concentrations reaching up to 6.1 μg/kg dry weight [39]. More concerning are findings from biomonitoring studies: breast milk samples from women in Jakarta and Purwakarta showed detectable levels of multiple PFAS including PFOS (found in all twenty women sampled), PFHxS (detected in 45% of samples), perfluorononanoic acid (PFNA), and perfluoroheptanoic acid (PFHpA) [39]. The average PFOS concentration in Indonesian breast milk was 84 parts per trillion (ppt), more than four times higher than the drinking water health advisory limit of 20 ppt for combined PFOA, PFOS, PFHxS, PFHpA, and PFNA established in some jurisdictions, with individual samples exceeding this threshold by more than twelve-fold [39].

Major sources of PFAS contamination in Indonesia are diverse and reflect the country's industrial profile. Manufacturing facilities producing textiles, leather goods, food packaging materials, and non-stick coatings represent significant point sources, particularly in industrial zones such as those in West Java and East Java [40, 41]. Firefighting training activities at airports and military installations, where aqueous film-forming foams (AFFF) containing PFAS have been extensively used, constitute another important source category [4]. A comprehensive product testing study found that 62% of Indonesian samples analyzed—including clothing items and food packaging materials—contained elevated levels of PFAS above safety limits proposed by the European Union for consumer products [40, 41]. The widespread use of PFAS-containing products in Indonesian households, combined with inadequate waste management infrastructure, creates diffuse sources through landfill leachate and improper disposal [8].

The environmental persistence of PFAS poses particular challenges in tropical aquatic ecosystems. The strong carbon-fluorine bonds resist hydrolysis, photolysis, and microbial degradation processes that typically attenuate other organic contaminants [5]. This persistence, combined with the water solubility of many PFAS, facilitates their transport through hydrological systems and accumulation in both sur-

Table 3. Selected pharmaceuticals and personal care products (PPCPs) detected in Indonesian aquatic environments.

Location	Matrix	Compound(s)	Concentration/ Load	Reference
Upper Citarum River Basin (UCRB)	River basin (total load)	Paracetamol; Amoxicillin	426.1 tons/year; 343.7 tons/year	[13]
Cirata Reservoir, West Java	Reservoir water	14 antibiotics (ciprofloxacin, enrofloxacin, sulfamethoxazole, trimethoprim, oxytetracycline, etc.)	Higher in wet season; livestock farming primary source	[19]
Jakarta Bay (Angke, Ancol)	Coastal seawater	Paracetamol	Angke: 610 ng/L; Ancol: 420 ng/L	[21]
Central Java coastal aquaculture	Aquaculture water	Acetaminophen (ACM); Oxytetracycline (OTC)	ACM: up to 5.5±1.9 ng/L (Brebes); OTC: up to 8.0±3.3 ng/L	[23]
Surabaya, East Java	Septic tanks; Surabaya River	Paracetamol; Caffeine	Septic: 15.54 mg/L; River: 10.31 mg/L (caffeine)	[37]
Jakarta rivers	River water	Bisphenol A (BPA)	50–8,000 ng/L	[38]
Ciliwung River, Jakarta	River (mass flux)	Multiple PPCPs (DEET, personal care products)	5–17 tons/year of quantified pollutants	[15]
Jakarta rivers	River water	71 organic contaminants (flame retardants, PCPs, pharmaceuticals)	High concentrations from municipal wastewater	[20]

Notes: DEET = N,N-diethyl-m-toluamide; PCPs = personal care products. Concentrations and loads represent ranges or mean values as reported in cited studies.

face and groundwater [8]. Long-chain PFAS such as PFOS and PFOA also exhibit bioaccumulation potential, concentrating in aquatic organisms and potentially biomagnifying through food webs [31]. The implications for Indonesian fisheries and aquaculture—sectors employing millions and providing primary protein sources for the population—are concerning but remain inadequately characterized [6].

Despite growing international recognition of PFAS risks, Indonesia currently lacks specific regulations addressing these substances in environmental media or establishing maximum allowable concentrations in drinking water [39]. PFAS are essentially absent from national monitoring programs, and analytical capacity to detect and quantify these compounds at environmentally relevant concentrations (often in the parts per trillion range) remains limited [39, 8]. This regulatory gap is particularly significant given that PFAS contamination in developing nations is projected to increase as industrialization continues, following patterns observed in China where rapid economic growth corresponded with escalating PFAS levels [6, 4]. The limited research base on PFAS in Indonesia and Southeast Asia more broadly—with approximately 90% of Asian PFAS studies originating from China, Japan, and South Korea [6]—underscores the urgent need for expanded monitoring, research on exposure pathways specific to Indonesian populations, and development of appropriate regulatory frameworks to address this class of persistent and potentially hazardous contaminants.

2.4 Pesticides and Agricultural Chemicals

Modern pesticides represent a significant class of emerging contaminants in Indonesian aquatic environments, driven by the country's role as a major agricultural producer and the intensification of farming practices over recent decades [11, 43]. While legacy organochlorine pesticides such as DDT and its metabolites have been extensively studied and largely phased out, contemporary pesticide use has shifted toward organophosphates, pyrethroids, carbamates, neonicotinoids, and various herbicides [1]. These modern pesticides, though generally less persistent than their predecessors, can still pose significant risks to aquatic ecosystems and human health, particularly when inadequately managed or when applied in proximity to water bodies [48].

Organophosphate insecticides remain among the most

Table 4. Per- and polyfluoroalkyl substances (PFAS) detected in Indonesian environmental matrices and consumer products.

Location/ Sample Type	Matrix	PFAS Compound(s)	Concentration/ Detection	Reference
Jakarta Bay (2004 data)	Sediment	PFOS; PFOA	PFOS: detected in all samples; PFOA: up to 6.1 μg/kg dry weight	[39]
Jakarta and Purwakarta	Breast milk	PFOS; PFHxS; PFNA; PFHpA	PFOS: 84 ppt average (all 20 women sampled); PFHxS: 45% detection frequency	[39]
Indonesia (national)	Consumer products (clothing, food packaging)	Total PFAS	62% of samples had high PFAS levels above EU safety limits	[40]
Indonesia (national)	Various products	PFOS; PFOA	Detected in textiles, leather, food packaging	[41]

Notes: PFOS = perfluorooctanesulfonic acid; PFOA = perfluorooctanoic acid; PFHxS = perfluorohexane sulfonic acid; PFNA = perfluorononanoic acid; PFHpA = perfluoroheptanoic acid; ppt = parts per trillion. Vermont drinking water health advisory limit for combined PFAS: 20 ppt.

widely detected pesticide residues in Indonesian waters, despite growing concerns about their neurotoxicity and ecotoxicological impacts [43, 11]. Profenofos, chlorpyrifos, and acephate are commonly used in rice cultivation and vegetable farming, with detection frequencies varying by region and agricultural intensity [42]. A comprehensive study of Rawa Pening Lake in Central Java, an important water body surrounded by intensive agricultural activities, revealed that profenofos was the most abundant organophosphate pesticide detected in both water and sediment samples, reflecting its widespread application in the surrounding paddy fields and vegetable farms [42]. The transport of these pesticides from agricultural lands to aquatic environments occurs primarily through surface runoff during rainfall events, with concentrations often peaking during the monsoon season when intense precipitation mobilizes pesticide residues from treated fields [44]. Given Indonesia's tropical climate with pronounced wet and dry seasons, this seasonal pulsing of pesticide contamination presents particular challenges for aquatic organisms adapted to relatively stable chemical environments.

Pyrethroid insecticides, including deltamethrin, cypermethrin, and cyhalothrin, have gained popularity as alternatives to organophosphates due to their perceived lower mammalian toxicity and rapid environmental degradation under ideal conditions [11]. These synthetic analogs of natural pyrethrins are extensively employed in Indonesian rice fields, where they target a range of insect pests including stem borers, leafhoppers, and planthoppers [11, 43]. However, pyrethroids exhibit high toxicity to aquatic invertebrates and fish, even at very low concentrations, and their degradation can be inhibited under conditions of low light and temperature—factors less problematic in tropical environments but still relevant during cloudy monsoon periods or in shaded waterways [48]. Carbamate insecticides, particularly carbofuran, also feature prominently in Indonesian agricultural practices, especially in rice and maize cultivation [11, 42]. The extensive monitoring of pesticide residues across Indonesian agricultural commodities and environmental matrices has documented the presence of carbamate, pyrethroid, and organophosphate residues in rice, soybeans, vegetables, paddy water, river water, lake water, and even marine waters, indicating the widespread spatial extent of pesticide contamination (Table 5) [43].

Herbicides constitute another important category of pesticide contamination in Indonesian waters, with compounds such as glyphosate, paraquat, and 2,4-D being widely applied for weed control in plantations, rice fields, and along infrastructure corridors [1]. Glyphosate, the world's most widely used herbicide, is extensively employed in Indonesian oil palm and rubber plantations, as well as in rice farming systems [11]. While glyphosate is often characterized as having relatively low acute toxicity to vertebrates, concerns have emerged regarding its effects on aquatic microbial communities, its potential endocrine-disrupting properties, and the toxicity of its degradation products and formulation adjuvants [48]. Paraquat, despite being banned or restricted in many countries due to its extreme human toxicity and environmental persistence, continues to be used in some Indonesian agricultural contexts, posing risks to both applicators and aquatic ecosystems receiving runoff from treated areas [43].

Neonicotinoid insecticides, a relatively newer class of systemic pesticides that act on insect nicotinic acetylcholine receptors, have gained market share in recent years due to their effectiveness against sucking and chewing insects and their systemic properties allowing plant uptake and translocation [11]. Imidacloprid, thiamethoxam, and clothianidin are among the neonicotinoids used in Indonesian agriculture, particularly in rice, horticulture, and plantation crops. These compounds are highly water-soluble, facilitating their transport in aquatic systems, and have been implicated in declines of beneficial insects including pollinators globally

Table 5. Pesticides detected in Indonesian aquatic environments.

Location	Matrix	Pesticide Type/ Compound	Key Findings	Reference
Rawa Pening Lake, Central Java	Water and sediment	Organophosphates (profenofos highest); Organochlorines	Profenofos most abundant; used in paddy and vegetable fields	[42]
Indonesia (nationwide)	Rice, soybeans, vegetables, paddy water, river water, lake water, sea water	Organochlorines, organophosphates, carbamates, pyrethroids	Residues detected in multiple environmental matrices and food commodities	[43]
Southeast Asia/ Indonesia	Paddy fields	Carbofuran (carbamate); Deltamethrin (pyrethroid); Chlorpyrifos (OP)	Widely employed in Indonesian rice fields	[11]
Opak Watershed, Java	Agricultural runoff to river	Organophosphate residues	Runoff containing OP residues reduces river water quality	[44]

Notes: OP = organophosphate. Data compiled from studies examining pesticide contamination in various Indonesian agricultural regions and water bodies.

[48]. Their sub-lethal effects on aquatic invertebrates and potential for bioaccumulation in aquatic food webs warrant greater research attention in the Indonesian context, where such studies remain limited [30, 1].

Regional variation in pesticide types and contamination patterns reflects Indonesia's diverse agricultural landscape. In the intensive rice-growing regions of Java, organophosphates, carbamates, and pyrethroids dominate, with peak concentrations associated with planting and pre-harvest application periods [11, 43]. The vast oil palm plantations of Sumatra and Kalimantan contribute herbicides (particularly glyphosate and paraquat) and insecticides targeting specific plantation pests, while highland vegetable-growing areas employ diverse pesticide cocktails including fungicides alongside insecticides and herbicides [42, 44]. This spatial heterogeneity in pesticide use patterns necessitates region-specific monitoring and management strategies that account for local agricultural practices, cropping calendars, and hydrological characteristics.

Despite the documented presence of pesticide residues in various Indonesian environmental matrices, significant knowledge gaps remain regarding their long-term ecological impacts, mixture toxicity effects when multiple pesticides co-occur, and human health risks from chronic low-level exposure through drinking water and food [1, 30]. Furthermore, although some pesticide residues in food commodities remain below maximum residual limits established by Indonesian national standards, concentrations are sometimes close to these thresholds, and standards for many newer pesticides and their metabolites have yet to be established [43]. The detection of pesticide residues even after organochlorine insecticides were banned highlights the persistence of these legacy contaminants, while the continued detection of currently-used pesticides underscores the ongoing nature of agricultural contamination [43, 48]. Addressing pesticide contamination in Indonesian waters will require integrated approaches encompassing improved application practices, buffer zones to protect water bodies, promotion of integrated pest management strategies that reduce chemical dependency, and enhanced regulatory oversight and enforcement of pesticide registration and use regulations.

2.5 Industrial Chemicals and Endocrine Disrupting Chemicals (EDCs)

Industrial chemicals with endocrine-disrupting properties represent a particularly insidious class of emerging contaminants in Indonesian aquatic environments, as these compounds can interfere with hormonal systems of exposed organisms at extremely low concentrations, often in the parts per trillion range [5, 4]. Endocrine disrupting chemicals (EDCs) encompass a diverse array of substances including plasticizers (phthalates, bisphenols), flame retardants (polybrominated diphenyl ethers or PBDEs), alkylphenols and their ethoxylates (nonylphenol, octylphenol), organotins, and various industrial intermediates and by-products [6, 8]. These compounds are ubiquitous in modern industrial societies, incorporated into plastics, electronics, textiles, construction materials, and consumer products, with subsequent release to the environment through manufacturing processes, product degradation, and waste disposal [31]. The endocrine-disrupting effects—including reproductive impairment, developmental abnormalities, immune system dysfunction, and metabolic disorders—have been documented across multiple taxonomic groups, raising concerns about population-level impacts on aquatic biodiversity and potential human health risks through environmental exposure pathways [4, 5].

Phthalates, a group of diesters of phthalic acid used primarily as plasticizers to impart flexibility to polyvinyl chloride (PVC) products, rank among the most frequently detected EDCs in Indonesian environmental waters [20, 17]. Dimethyl phthalate (DMP), diethyl phthalate (DEP), di-n-butyl phthalate (DBP), and di(2-ethylhexyl) phthalate (DEHP) have been identified in rivers, coastal waters, and sediments,

Table 6. Emerging contaminant concentrations and loads at major Indonesian pollution hotspots.

Hotspot Location	Contaminant Category	Specific Compound(s)	Concentration/ Load	Reference
Upper Citarum River Basin	PPCPs	Paracetamol	426.1 tons/year	[13]
	PPCPs	Amoxicillin	343.7 tons/year	[13]
	PPCPs	14 antibiotics	Higher in wet season	[19]
	Microplastics	Various polymers	High loads (world's most polluted river)	[2]
Jakarta Bay	PPCPs	Paracetamol	Angke: 610 ng/L; Ancol: 420 ng/L	[21]
	PFAS	PFOS	All sediment samples positive	[39]
	PFAS	PFOA	Up to 6.1 μg/kg (sediment)	[39]
	Microplastics	PE fragments	300–500 μm (dominant)	[35]
	Multiple	71 organic contaminants	High concentrations	[20]
	EDCs	Bisphenol A	50–8,000 ng/L	[38]
Ciliwung River (Jakarta)	Multiple	Organic pollutants	5–17 tons/year (mass flux)	[15]
	PPCPs	DEET, PCPs	70–80% from municipal sewage	[15]
Lake Rawapening (Central Java)	Pesticides	Profenofos (OP)	Most abundant in water & sediment	[42]
	Nutrients	N, P	Severe eutrophication	[45]
Surabaya (East Java)	PPCPs	Paracetamol	15.54 mg/L (septic tanks)	[37]
	PPCPs	Caffeine	10.31 mg/L (Surabaya River)	[37]
Central Java coastal aquaculture	PPCPs	Acetaminophen (ACM)	Up to 5.5±1.9 ng/L (Brebes)	[23]
	PPCPs	Oxytetracycline (OTC)	Up to 8.0±3.3 ng/L	[23]

Notes: PPCPs = pharmaceuticals and personal care products; PFAS = per- and polyfluoroalkyl substances; PFOS = perfluorooctanesulfonic acid; PFOA = perfluorooctanoic acid; PE = polyethylene; EDCs = endocrine disrupting chemicals; DEET = N,N-diethyl-m-toluamide; PCPs = personal care products; OP = organophosphate; N = nitrogen; P = phosphorus. Data compiled from cited studies examining specific hotspot locations.

with concentrations often correlating with industrial discharge points and urban population density [15]. Studies in Jakarta Bay and surrounding coastal areas have documented the widespread occurrence of multiple phthalate compounds, reflecting the extensive use of PVC materials in Indonesian manufacturing and construction sectors, as well as their incorporation into personal care products, medical devices, and food packaging [16]. DEHP, classified as a priority pollutant due to its suspected carcinogenic properties and demonstrated reproductive toxicity in laboratory studies, has been detected in both dissolved and particulate phases in Indonesian marine environments, with sediments serving as important reservoirs where phthalates can accumulate and persist [20]. The lipophilic nature and persistence of certain phthalates facilitate their bioaccumulation in aquatic organisms, though biotransformation and excretion processes limit biomagnification through food webs for most compounds in this class [17].

Bisphenol A (BPA), an industrial chemical used extensively in the production of polycarbonate plastics and epoxy resins lining food and beverage containers, represents another well-studied EDC of concern globally, though research specific to Indonesian environmental concentrations remains limited [16, 25]. BPA exhibits estrogenic activity and has been associated with reproductive abnormalities, developmental effects, and metabolic disorders in wildlife and laboratory animals exposed during critical developmental windows [23]. Environmental sources include leaching from plastic products, discharge from manufacturing facilities, and release during waste incineration, with wastewater treatment plants serving as major point sources where incomplete removal allows BPA passage into receiving waters [4]. Recent regula-

Table 7. Characteristics and pollution profiles of major Indonesian river hotspots.

River/ Basin	Location	Population Served (million)	Major Pollution Sources	Dominant Contaminants
Citarum	West Java	>15	2,000+ industries (textile, pharmaceutical, food processing); intensive agriculture; urban wastewater	PPCPs, microplastics, EDCs, heavy metals, pesticides
Ciliwung	Jakarta	>10	Municipal sewage (30 million metro area); industrial discharge; solid waste	PPCPs (DEET), microplastics, EDCs (BPA), multiple organics
Brantas	East Java (Surabaya)	>8	Urban domestic wastewater; industrial zones; agricultural runoff	PPCPs, pesticides, industrial chemicals
Surabaya River	East Java	>3	Septic tank effluents; domestic wastewater; urban runoff	PPCPs (paracetamol, caffeine)
Code	Yogyakarta	>1	Urban wastewater; small industries; domestic discharge	PPCPs, urban pollutants
Solo	Central Java	>5	Multiple cities discharge; agricultural runoff; domestic wastewater	PPCPs, pesticides, nutrients

Notes: Population served represents approximate number of people dependent on the river for various purposes (drinking water, irrigation, livelihoods). EDCs = endocrine disrupting chemicals; PPCPs = pharmaceuticals and personal care products; BPA = bisphenol A; DEET = N,N-diethyl-m-toluamide.

tory actions in various countries restricting BPA use in certain consumer products (particularly infant bottles and food contact materials) have driven substitution toward alternative bisphenols such as bisphenol S (BPS) and bisphenol F (BPF), though emerging evidence suggests these replacements may exhibit similar endocrine-disrupting properties, highlighting the challenge of regrettable substitution in chemical management [5, 6].

Alkylphenols, particularly nonylphenol (NP) and octylphenol (OP), constitute another important EDC category detected in Indonesian waters [20, 15]. These compounds are primarily environmental degradation products of alkylphenol ethoxylates (APEs), which are widely used as non-ionic surfactants in industrial processes, detergents, and emulsifiers [17]. Paradoxically, the biodegradation of APEs under anaerobic conditions prevalent in sediments and inadequately aerated wastewater treatment systems produces nonylphenol and octylphenol, which are more persistent and more potently estrogenic than their parent compounds [16]. Nonylphenol has been detected in Indonesian coastal sediments and waters at concentrations raising concern for benthic organism exposure, with documented effects in aquatic organisms including feminization of male fish, impaired reproduction, and altered sex ratios in populations [20, 15]. The textile industry, which represents a significant manufacturing sector in Indonesia particularly in Java, is a notable source of APE and alkylphenol contamination through discharge of processing chemicals used in dyeing and finishing operations [13].

Flame retardants, particularly polybrominated diphenyl ethers (PBDEs), have emerged as global contaminants of concern due to their persistence, bioaccumulative properties, and potential endocrine-disrupting and neurotoxic effects [8, 6]. These brominated compounds have been extensively incorporated into electronics, textiles, furniture foams, and building materials to meet flammability standards, with subsequent environmental release occurring during product manufacturing, use, and disposal, particularly through improper electronic waste recycling and open burning practices [31]. Indonesia's growing electronics manufacturing sector and role as a destination for electronic waste imports raise concerns about PBDE contamination, though systematic environmental monitoring data for these compounds remains scarce compared to more extensively studied regions [5]. The chemical structure and properties of PBDEs—including their lipophilicity, resistance to degradation, and tendency to bioaccumulate and biomagnify through aquatic food webs—parallel those of legacy persistent organic pollutants such as PCBs, suggesting potential for long-term environmental persistence and biological impacts [4].

Organotin compounds, particularly tributyltin (TBT) and triphenyltin (TPT), represent a unique EDC category historically used as biocides in marine antifouling paints and fungicides in agriculture [21, 22]. Despite international restrictions on TBT use in antifouling coatings following recognition of its severe impacts on non-target marine organisms—including imposex (masculinization) in female gastropods at parts per trillion concentrations and immunotoxicity in various taxa—organotin contamination persists in Indonesian harbors, ports, and coastal waters due to continued leaching from older vessel hulls and sediment reservoirs [21]. Studies in Indonesian waters have documented TBT and degradation products (dibutyltin, monobutyltin) in sediments and biota from commercial ports and shipyards, reflecting both historical contamination and potentially ongoing inputs from vessels painted before restrictions were implemented or from illegal continued use [22]. The exceptional potency of TBT as an endocrine disruptor, combined with its persistence in anaerobic sediments where degradation proceeds slowly, creates long-term exposure scenarios for benthic organisms even after source reduction measures are enacted [4].

The ecological and human health implications of EDC contamination in Indonesian aquatic environments remain inadequately characterized despite growing evidence of widespread occurrence [5, 1]. Wildlife studies conducted in other regions have documented associations between environmental EDC exposure and reproductive impairment, population declines, immune dysfunction, and developmental abnormalities across fish, amphibians, reptiles, birds, and mammals [4, 6]. The particular vulnerability of Indonesia's rich aquatic biodiversity—including endemic species adapted to specific ecological niches that may be particularly sensitive to hormonal disruption—warrants precautionary attention [9]. From a human health perspective, exposure pathways include consumption of contaminated drinking water and seafood, dermal contact with contaminated waters during bathing or occupational activities, and indirect exposure through bioaccumulation in food chains [8]. Epidemiological associations between EDC exposure and various adverse human health outcomes including reproductive disorders, metabolic diseases, and developmental effects have been reported in international literature, though establishing causality remains challenging and exposure-response relationships may be non-monotonic for some endocrine-active compounds [5, 31].

Addressing EDC contamination requires comprehensive strategies spanning regulatory frameworks, source reduction, improved waste management, and enhanced environmental and biomonitoring [1, 13]. Establishing water quality standards and environmental quality guidelines for priority EDCs, informed by ecotoxicological research on species relevant to Indonesian ecosystems, would provide regulatory benchmarks for environmental management [4]. Promoting alternatives to EDC-containing products through green chemistry initiatives and safer chemical substitution programs can reduce environmental releases while avoiding regrettable substitution toward equally problematic compounds [6]. Wastewater treatment infrastructure capable of removing trace organic contaminants through advanced processes including activated carbon adsorption, advanced oxidation, and membrane filtration represents a critical investment for reducing EDC inputs to aquatic environments, though cost considerations and technical capacity requirements must be addressed in the Indonesian context [16, 29]. Finally, expanded environmental monitoring programs incorporating sensitive analytical methods for detecting EDCs at environmentally relevant concentrations, coupled with biomonitoring approaches assessing actual biological exposures and effects in indicator species, are essential for characterizing contamination trends, evaluating management effectiveness, and protecting Indonesia's aquatic resources from this diverse class of hormonally active contaminants [5, 8].

3. GEOGRAPHIC HOTSPOTS AND CASE STUDIES

While emerging contaminant contamination has been documented across Indonesian aquatic environments, certain geographic areas stand out as critical hotspots where pollution concentrations, diversity of contaminants, and ecosystem impacts are particularly severe (Tables 6 and 7). These hotspots typically coincide with densely populated urban centers, intensive industrial zones, and areas of concentrated agricultural activity where inadequate wastewater treatment infrastructure, poor waste management practices, and proximity to sensitive aquatic ecosystems create conditions conducive to severe contamination. This section presents case studies from Indonesia's most studied and critically impacted aquatic environments, examining contamination profiles, pollution sources, and environmental consequences. Understanding the characteristics of these hotspots provides valuable insights into contamination patterns, identifies priority areas for intervention, and offers lessons applicable to other similarly threatened water bodies across the archipelago.

3.1 Citarum River Basin: Indonesia's Most Polluted River

The Citarum River Basin in West Java represents perhaps Indonesia's most emblematic case of severe aquatic pollution and has gained international notoriety as one of the world's most contaminated rivers [13, 14]. Stretching approximately 300 kilometers from its headwaters at Mount Wayang to its discharge into the Java Sea, the Citarum traverses one of Indonesia's most densely populated and heavily industrialized regions, supporting over 15 million people who depend on the river for drinking water, irrigation, and livelihoods [19]. The Upper Citarum River Basin alone hosts more than 2,000 industrial facilities—including textile manufacturers, food processing plants, chemical producers, and pharmaceutical companies—alongside intensive agricultural operations and rapidly expanding urban settlements, creating an overwhelming burden of industrial, agricultural, and domestic pollution that has severely degraded water quality throughout the basin [13].

Emerging contaminant pollution in the Citarum River system is extensive and diverse, reflecting the multiplicity of pollution sources. Pharmaceutical contamination is particularly severe, with an estimated 426.1 tons of paracetamol and 343.7 tons of amoxicillin entering the Upper Citarum River Basin annually from improper disposal of unused medicines, pharmaceutical industry discharges, and inadequately treated domestic and hospital wastewater [13]. The Cirata Reservoir, a major water body within the Citarum Basin serving multiple purposes including drinking water supply, irrigation, and one of Southeast Asia's largest floating cage aquaculture operations, receives inputs of at least 14 different antibiotics from human use, livestock farming, and aquaculture activities, with concentrations higher during wet seasons when rainfall mobilizes contaminants from the surrounding catchment [19]. Antibiotic-resistant bacteria, including antibiotic-resistant *Escherichia coli*, have been detected throughout the Upper Citarum River, with erythromycin-resistant strains dominating but tetracycline-resistant and extended-spectrum β-lactamase-producing *E. coli* serving as suitable indicators for overall antibiotic resistance contamination [14].

Microplastic contamination further compounds the pollution burden, with the Citarum River exhibiting particularly high microplastic loads as plastic waste from households, industries, and inadequate waste management infrastructure fragments and accumulates in the water column and sediments [2, 1, 49]. Studies characterizing microplastics in Upper Citarum sediments and macrozoobenthos have revealed widespread contamination affecting benthic communities and demonstrating direct exposure pathways through the food web [49]. Industrial chemicals including endocrine-disrupting compounds, heavy metals, phthalates, and complex organic pollutant mixtures have been documented in various reaches of the river, with concentrations in some industrial discharge zones approaching or exceeding those found in untreated industrial wastewater [38]. Phthalate contamination in Citarum groundwater and surface water poses both carcinogenic and non-carcinogenic health risks to communities relying on these water sources [50]. The cumulative effect of this multi-source, multi-contaminant pollution has been catastrophic for aquatic life, with fish populations severely depleted, benthic invertebrate communities simplified and dominated by pollution-tolerant taxa, and overall ecosystem function fundamentally altered [19].

The Indonesian government has recognized the Citarum crisis and launched the Citarum Harum ("Fragrant Citarum") program in 2018, a comprehensive initiative involving military deployment, industrial compliance enforcement, waste management improvements, and wastewater treatment infrastructure development aimed at restoring the river to acceptable water quality standards within seven years. While this high-profile effort has achieved some visible successes in removing accumulated solid waste and closing or relocating non-compliant industries, fundamental challenges remain regarding long-term financing for wastewater treatment infrastructure, ensuring sustained compliance from thousands of small and medium enterprises, changing waste disposal behaviors among millions of residents, and addressing the legacy contamination accumulated in sediments over decades of intensive pollution [13]. The Citarum case illustrates both the severity of emerging contaminant pollution in Indonesia's industrialized river basins and the complexities of remediation in contexts where pollution sources are numerous, diverse, and deeply embedded in regional economic and social systems.

3.2 Jakarta Bay and Coastal Marine Environments

Jakarta Bay, located on the northern coast of Java and receiving discharge from thirteen rivers draining the Indonesian capital and its surrounding industrial hinterland, represents Indonesia's most studied marine pollution hotspot and exemplifies the challenges facing coastal ecosystems adjacent to megacities in developing nations [20, 15]. With a population exceeding 30 million in the greater Jakarta metropolitan area and only minimal wastewater treatment infrastructure, the rivers flowing into Jakarta Bay transport enormous quantities of untreated domestic sewage, industrial effluents, and solid waste, creating a nearshore marine environment characterized by degraded water quality, depleted dissolved oxygen, elevated nutrient concentrations, and severe contamination with diverse emerging contaminants [21].

Microplastic contamination in Jakarta Bay has been extensively documented, with estuarine studies revealing that rivers draining different parts of the metropolitan area contribute varying microplastic loads based on upstream population density and waste management adequacy [35]. The Dadap River exhibited the highest microplastic abundance among nine studied estuaries, while the spatial pattern of contamination followed the order North Jakarta > Tangerang > Bekasi, reflecting differences in urbanization intensity and proximity to industrial zones [35]. Seasonal variability in microplastic release from the Greater Jakarta area to Jakarta Bay has been observed, with precipitation patterns influencing transport dynamics and concentrations exhibiting heterogeneity related to monsoon cycles [51]. Polyethylene fragments in the 300–500 μm size range dominated the microplastic composition, indicating significant contribution from fragmentation of consumer plastic waste [35]. Protected areas including wildlife reserves, Ramsar sites, and national parks in northern Jakarta and Kepulauan Seribu have also been found to contain substantial microplastic burdens, demonstrating that even conservation areas are not immune to this pervasive contamination [52]. Microplastic contamination extends beyond the water column into seafood, with Indonesian anchovies harvested from waters including Jakarta Bay containing substantial microplastic burdens averaging hundreds of particles per individual fish [36]. Research on bacterial communities in Jakarta Bay has identified microorganisms capable of degrading polyethylene and polyethylene terephthalate, suggesting potential for bioremediation approaches though practical application remains in early stages [53].

Pharmaceutical and personal care product contamination in Jakarta Bay reflects the massive population served by inadequately treated wastewater systems [21]. Paracetamol has been detected at particularly high concentrations, with measurements of 610 ng/L at Angke and 420 ng/L at Ancol—levels substantially higher than those reported from most other developing nation coastal waters and raising concerns about chronic exposure effects on nearshore marine organisms and impacts on shellfish farming operations that provide livelihoods for coastal communities [21]. Comprehensive screening studies have identified 71 different organic contaminants in Jakarta surface waters, including flame retardants, personal care product ingredients, and various pharmaceutical drugs, with compounds originating from municipal wastewater discharges detected in particularly high concentrations [20].

Per- and polyfluoroalkyl substances have been detected in Jakarta Bay sediments, with 2004 sampling revealing PFOS in all analyzed samples and PFOA concentrations reaching up to 6.1 μg/kg dry weight, providing evidence of long-term PFAS contamination from industrial sources, consumer product degradation, and firefighting activities at the adjacent international airport [39]. The Ciliwung River, Jakarta's largest urban river, transports an estimated 5–17 tons per year of quantified organic pollutants into the bay, with municipal sewage constituents making up 70–80% of these fluxes and personal care product ingredients such as the insect repellent DEET exhibiting particularly high mass flux rates [15].

Beyond Jakarta Bay, other Indonesian coastal areas face similar though often less intensively studied contamination challenges. The north coast of Central Java, where aquaculture activities concentrate, has documented emerging contaminant contamination including pharmaceuticals detected in water samples from shrimp farming areas, with oxytetracycline presenting high ecological risks to algae [23]. Surabaya's coastal waters receive contamination from the densely populated metropolitan area, with septic tank effluents containing extremely high paracetamol concentrations (15.54 mg/L) and the Surabaya River exhibiting elevated caffeine levels (10.31 mg/L) that ultimately discharge to coastal environments [37]. These coastal pollution hotspots highlight the vulnerability of Indonesia's valuable marine resources—including fisheries, aquaculture, coral reefs, and mangrove ecosystems—to land-based sources of emerging contaminant pollution.

3.3 Lakes and Reservoirs as Sentinel Systems

Indonesian lakes and reservoirs serve as important sentinel systems for detecting emerging contaminant pollution, as these relatively enclosed water bodies integrate contamination from their catchments and retain pollutants in ways that can reveal long-term accumulation patterns [42]. Lake Rawapening (Rawa Pening) in Central Java exemplifies the pesticide contamination challenges facing lakes surrounded by intensive agricultural activities [42, 45]. Survey data revealed that profenofos, an organophosphate insecticide widely applied in the surrounding paddy fields and vegetable farms, was the most abundant pesticide detected in both lake water and sediment samples, reflecting its extensive use and transport from agricultural lands via surface runoff during rainfall events [42]. Beyond pesticides, Lake Rawapening faces severe eutrophication driven by excessive nitrogen and phosphorus inputs from agricultural fertilizers and domestic wastewater, with nutrient pollution compounding the challenges posed by chemical contaminants and resulting in dense algal blooms, oxygen depletion, and degraded ecosystem health [45].

The Cirata Reservoir in the Citarum Basin, already discussed as part of the broader Citarum contamination complex, demonstrates how multipurpose water bodies face compounding pollution pressures from diverse sources [19]. Serving simultaneously as a drinking water source for millions, a major irrigation supply, a hydroelectric power generation site, and home to Indonesia's largest floating cage aquaculture industry producing approximately 90,000 tons of tilapia and carp annually, the reservoir receives antibiotic contamination from all these sectors: human pharmaceutical use and hospital discharges from upstream urban areas, veterinary antibiotics from livestock farming operations in the catchment, and prophylactic and therapeutic antibiotics applied directly to aquaculture cages [19]. Modeling studies indicate that livestock farming—particularly sheep, cattle, and broiler operations—represents the primary source of antibiotic inputs, with higher loads occurring during the wet season when rainfall mobilizes manure-associated antibiotics from agricultural lands and transports them via tributary rivers into the reservoir [19].

Lake Toba in North Sumatra, Southeast Asia's largest lake and an important tourism destination, faces emerging pressures from expanding aquaculture operations, with fish farming in floating net cages potentially introducing veterinary pharmaceuticals and contributing to nutrient loading, though comprehensive studies on emerging contaminant contamination in this iconic water body remain limited in the published literature. Urban reservoirs such as Saguling and Jatiluhur in West Java, which provide drinking water for Jakarta and irrigation for extensive agricultural areas, represent particularly critical systems where emerging contaminant contamination could have far-reaching public health and food security implications, highlighting the urgent need for comprehensive monitoring and pollution prevention strategies targeting these valuable freshwater resources.

3.4 Industrial Zones and Urban Rivers

Indonesia's rapid industrialization has created numerous concentrated pollution hotspots where manufacturing activities generate complex mixtures of emerging contaminants that challenge receiving water bodies' assimilative capacity [38]. The Cikarang industrial estate in West Java, recognized as one of Southeast Asia's largest industrial zones, hosts thousands of manufacturing facilities producing electronics, textiles, chemicals, pharmaceuticals, automotive components, and consumer goods, with inadequately treated industrial wastewater from this concentrated manufacturing complex severely impacting downstream water quality in rivers ultimately discharging to Jakarta Bay [20].

The textile industry, particularly concentrated in West Java and employing hundreds of thousands of workers, represents a significant source of complex organic pollution including dyes, surfactants, sizing agents, and finishing chemicals that contribute to the severe contamination documented in rivers such as the Citarum [38]. Targeted and non-targeted analytical approaches using advanced mass spectrometry have identified numerous dye compounds and chemical contaminants in heavily polluted Indonesian rivers, demonstrating the chemical complexity of industrial wastewater impacts [54]. Alkylphenol ethoxylates used as non-ionic surfactants in textile processing degrade under anaerobic conditions to form the more persistent and more estrogenic nonylphenol and octylphenol, which accumulate in sediments and exhibit endocrine-disrupting effects on aquatic organisms [13]. Paper manufacturing facilities, identified through chemical fingerprinting studies, release characteristic compounds including bisphenol A—detected at concentrations of 50–8,000 ng/L in Jakarta industrial area rivers, comparable to levels in untreated paper industry wastewater [38]. Environmental risk assessments of sediments from Jakarta's tropical coastal megacity environment have documented priority and emerging organic pollutants at levels posing significant ecological risks [55].

Urban rivers beyond Jakarta face similar though variably studied contamination challenges. The Brantas River in East Java, flowing through multiple cities including Surabaya (Indonesia's second-largest city), receives diverse pollution inputs from urban domestic wastewater, industrial discharges, and agricultural runoff from upstream rice-growing areas, creating a complex contamination profile that includes pesticides, pharmaceuticals, and industrial chemicals. Spatiotemporal studies of microplastic occurrence in Brantas River freshwater fish have documented seasonal and spatial patterns in contamination, with higher levels detected during certain periods and in specific river reaches reflecting pollution source dynamics [56]. The Jagir Estuary in Surabaya shows substantial microplastic pollution in sediments, demonstrating the transport of plastic waste from urban sources to coastal environments [57]. Aquaculture-rich coastal regions in East Java, such as Gresik, also exhibit microplastic contamination that may impact the productivity and safety of cultured seafood products [58]. Green mussels harvested from the Kalirejo coastal area in East Java contain microplastics, raising concerns about human dietary exposure through shellfish consumption [59]. The Code River in Yogyakarta, the Solo River draining Central Java, and various other urban waterways throughout the archipelago exhibit emerging contaminant contamination reflecting local industrial profiles, population densities, and wastewater management capacities, though comprehensive characterization remains limited for most systems outside the intensively studied Citarum and Jakarta areas.

The geographic concentration of Indonesia's emerging contaminant hotspots in Java, where the majority of studies have been conducted, reflects both the island's exceptional population density and industrial intensity and the concentration of research capacity in Javanese institutions. However, this geographic bias in research effort should not be interpreted to mean that contamination is absent from other islands. Eastern Indonesia, Sumatra, Kalimantan, and Sulawesi all face growing industrialization, urbanization, and agricultural intensification that likely generate similar emerging contaminant pollution, albeit with different specific profiles reflecting regional economic activities and environmental conditions. Expanding research attention to these understudied regions represents a critical priority for comprehensively assessing Indonesia's emerging contaminant challenge.

4. MANAGEMENT, REGULATION, AND TREATMENT APPROACHES

Addressing emerging contaminant pollution in Indonesian aquatic environments requires a comprehensive management framework encompassing regulatory standards, monitoring programs, treatment technologies, and remediation initiatives. However, Indonesia's current approach to managing emerging contaminants remains incomplete, with significant gaps in regulatory coverage, limited monitoring capacity, inadequate treatment infrastructure, and nascent remediation efforts that face substantial technical, financial, and institutional challenges. This section evaluates Indonesia's existing management and regulatory framework for water quality and emerging contaminants, assesses monitoring and analytical capabilities, reviews treatment technologies currently employed or under investigation, and examines major remediation initiatives including the high-profile Citarum Harum river cleanup program.

4.1 National Regulatory Framework and Standards

Indonesia's regulatory framework for water quality is anchored in the Environmental Protection and Management Law and implemented through various government regulations and ministerial decrees that establish water quality standards for different designated uses and set limits on wastewater discharges from various sources. The primary regulation governing water quality is Government Regulation No. 22 of 2021 concerning Environmental Protection and Management in Water Resources, which superseded previous regulations and established comprehensive water quality criteria for surface water, groundwater, and seawater based on designated use classifications. However, this regulatory framework was developed primarily to address conventional water quality parameters—including physical characteristics (temperature, turbidity), dissolved oxygen, nutrients (nitrogen, phosphorus), conventional organic matter (biochemical oxygen demand, chemical oxygen demand), pathogens (fecal coliform bacteria), and legacy contaminants such as heavy metals and certain persistent organic pollutants—rather than the diverse array of emerging contaminants that increasingly characterize Indonesian water pollution [1].

The vast majority of emerging contaminants discussed in this review—including most pharmaceuticals, personal care products, per- and polyfluoroalkyl substances, microplastics, and modern pesticides—are not explicitly addressed in Indonesian water quality standards or wastewater discharge regulations [39, 8]. For example, despite documented PFAS contamination in Jakarta Bay sediments and breast milk samples from Indonesian women, Indonesia currently lacks specific regulations establishing maximum allowable concentrations for PFAS in drinking water, surface water, or wastewater discharges [39]. Similarly, while pharmaceutical contamination has been extensively documented in the Citarum River Basin and Jakarta coastal waters, there are no regulatory limits for antibiotics, analgesics, or other pharmaceutical compounds in environmental waters, and no requirements for pharmaceutical manufacturers or healthcare facilities to implement specific treatment for removing active pharmaceutical ingredients from wastewater [13, 21]. Microplastics, despite their ubiquitous detection in Indonesian rivers, coastal waters, and seafood, are likewise absent from water quality standards, with no established monitoring protocols or regulatory thresholds [7].

Comparison with international regulatory frameworks highlights the extent of this gap. The European Union's Water Framework Directive establishes environmental quality standards for priority substances including several emerging contaminants and maintains a watch list of substances subject to EU-wide monitoring for potential future regulation [5, 6]. The United States Environmental Protection Agency's Contaminant Candidate List includes numerous emerging contaminants under consideration for potential drinking water regulation, with specific maximum contaminant levels established for several PFAS compounds in recent years [4]. WHO guidelines for drinking water quality provide health-based values for selected pharmaceuticals and pesticides, while various countries have established their own national standards for emerging contaminants based on precautionary approaches and emerging scientific evidence [8]. In contrast, Indonesia's regulatory framework has not kept pace with the evolving understanding of emerging contaminant risks, leaving a substantial gap between documented contamination and regulatory action [1].

Within ASEAN, efforts toward regional harmonization of environmental standards remain nascent, with individual member states adopting varying approaches to emerging contaminant regulation based on national priorities, technical capacities, and resources. Some Southeast Asian countries, particularly Singapore, have begun incorporating emerging contaminants into their monitoring programs and regulatory frameworks, while others including Indonesia rely primarily on conventional parameter monitoring [6]. The regulatory gaps create several problematic consequences: industries lack clear compliance targets for emerging contaminant discharges; wastewater treatment plant operators have no regulatory driver to invest in advanced treatment technologies capable of removing trace organic contaminants; monitoring programs focus on regulated parameters rather than emerging threats; and enforcement authorities lack legal basis to act against emerging contaminant pollution even where documented contamination poses environmental and health risks [13].

4.2 Monitoring Programs and Analytical Capabilities

Indonesia's capacity to monitor emerging contaminants in aquatic environments faces significant limitations in laboratory infrastructure, analytical expertise, spatial and temporal coverage, and systematic program design [1]. The Ministry of Environment and Forestry operates a national water quality monitoring program that regularly samples major rivers, lakes, and coastal waters for conventional parameters, generating data that inform water quality status assessments and pollution control priorities. However, this routine monitoring program does not systematically include emerging contaminants, reflecting both the absence of regulatory standards for these compounds and the analytical and financial challenges associated with detecting substances present at extremely low concentrations in complex environmental matrices [39].

Analytical detection of emerging contaminants requires sophisticated instrumentation capable of identifying and quantifying compounds at parts per trillion to parts per billion concentrations in water samples containing thousands of chemical constituents. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) and gas chromatography-mass spectrometry (GC-MS) represent the primary analytical platforms for pharmaceutical, pesticide, and industrial chemical analysis, while specialized techniques are required for PFAS (requiring specific LC-MS/MS methods) and microplastics (requiring microscopic examination, spectroscopic confirmation via FTIR or Raman spectroscopy, and specialized sample preparation to isolate particles from organic matter) [20, 15]. While major Indonesian research institutions and some government laboratories possess this equipment, analytical capacity remains concentrated in Java-based institutions, creating geographic disparities in monitoring capability and limiting systematic surveillance of emerging contaminants in other islands [7].

The limited emerging contaminant monitoring that has occurred in Indonesia has been driven primarily by research projects conducted by universities and research institutions rather than systematic regulatory surveillance programs [13, 14]. Studies documenting pharmaceutical contamination in the Citarum River, microplastic pollution in Jakarta Bay, PFAS in breast milk samples, and pesticide residues in Lake Rawapening represent discrete research investigations rather than components of ongoing monitoring programs designed to track temporal trends, assess spatial patterns, or evaluate effectiveness of management interventions [13, 35, 39, 42]. This research-driven rather than management-driven approach to emerging contaminant surveillance creates data that are valuable for characterizing the extent of contamination but insufficient for supporting systematic pollution control decision-making.

Quality assurance and quality control present additional challenges for emerging contaminant monitoring. The very low environmental concentrations of many emerging contaminants demand rigorous contamination prevention during sampling and analysis, careful attention to matrix effects that can suppress or enhance analytical signals, use of appropriate internal standards and surrogate compounds, and regular participation in proficiency testing programs to ensure analytical accuracy [20]. The costs associated with emerging contaminant analysis—including specialized consumables, instrument maintenance, and analyst training—further constrain monitoring capacity, particularly for resource-limited provincial and local government laboratories that may lack funding for routine emerging contaminant surveillance even if analytical equipment is available [1]. Developing sustainable, cost-effective monitoring strategies that balance the need for comprehensive surveillance against resource constraints represents a critical challenge for expanding Indonesia's emerging contaminant monitoring capacity.

4.3 Wastewater Treatment Technologies and Removal Efficiency

Indonesia's wastewater treatment infrastructure, where it exists, relies predominantly on conventional treatment technologies designed to remove biodegradable organic matter, suspended solids, pathogens, and nutrients rather than trace organic contaminants [1, 3]. Activated sludge systems, trickling filters, stabilization ponds (waste stabilization ponds or lagoons), and constructed wetlands represent the primary treatment technologies employed in Indonesian municipal and industrial wastewater treatment plants. While these conventional processes achieve substantial removal of biochemical oxygen demand, total suspended solids, and fecal bacteria, their effectiveness for removing emerging contaminants is highly variable and often incomplete [28, 29]. Case studies of sewerage treatment plants have demonstrated variable microplastic removal efficiencies, with substantial quantities still discharged in treated effluent highlighting the need for enhanced treatment processes [60]. The grey water footprint assessment comparing conventional pollution to micropollutants at Indonesian WWTPs reveals that emerging contaminants contribute disproportionately to environmental impacts despite their low concentrations [61].

Studies examining pharmaceutical removal in conventional wastewater treatment have demonstrated that while some compounds undergo significant biodegradation or sorption to biosolids (achieving 50–90% removal), others persist through treatment with minimal attenuation, resulting in treated effluent discharges that continue to introduce active pharmaceutical ingredients into receiving waters [13, 14]. For example, certain antibiotics including sulfamethoxazole and trimethoprim often exhibit incomplete removal in conventional activated sludge systems, while analgesics such as diclofenac similarly resist biodegradation and pass through treatment with limited attenuation [23]. Antimicrobial compounds like triclosan may achieve moderate removal through sorption to sludge, but degradation products can exhibit similar or even enhanced biological activity compared to parent compounds [17]. The fact that Indonesia's wastewater treatment infrastructure serves only a small fraction of the population—with estimates suggesting less than 10% of domestic wastewater receives any treatment before discharge—means that even the limited removal achieved by conventional treatment is available only for a minority of wastewater flows, while the vast majority enters aquatic environments with no treatment whatsoever [1, 3].

Advanced treatment technologies capable of achieving higher removal efficiencies for emerging contaminants exist but face implementation barriers in the Indonesian context related to capital costs, operating expenses, technical expertise requirements, and energy demands. Advanced oxidation processes (AOPs), which generate highly reactive hydroxyl radicals capable of degrading recalcitrant organic compounds, have demonstrated effectiveness for pharmaceutical removal in numerous studies and pilot applications [29]. Ozonation, UV/hydrogen peroxide treatment, and Fenton processes represent different AOP approaches, each with specific advantages and limitations regarding contaminant spectrum, cost, complexity, and by-product formation [16]. While some Indonesian wastewater treatment research has investigated catalytic ozonation-based AOPs for treating hospital and community health center wastewater, full-scale implementation remains limited [29].

Membrane technologies—including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—provide physical barriers that can effectively remove emerging contaminants based on molecular size, charge, and hydrophobicity. Reverse osmosis and nanofiltration achieve particularly high removal rates for most pharmaceuticals, pesticides, and industrial chemicals, while also providing excellent microplastic removal through size exclusion [5, 6]. However, membrane systems require substantial capital investment, consume significant energy for maintaining transmembrane pressure, generate concentrate streams requiring disposal, and demand regular maintenance including membrane cleaning and replacement [8]. These factors have limited membrane technology deployment primarily to specific applications such as drinking water treatment for high-value uses rather than widespread wastewater treatment.

Activated carbon adsorption, using either powdered activated carbon (PAC) dosed into treatment processes or granular activated carbon (GAC) in fixed-bed contactors, provides an effective and relatively proven technology for removing diverse organic micropollutants through adsorption to the carbon's extensive surface area [4]. Activated carbon treatment can be retrofitted to existing wastewater treatment plants by adding PAC dosing to biological treatment or installing GAC contactors as tertiary treatment, providing a potentially viable pathway for upgrading Indonesian facilities to address emerging contaminants [16]. Local production of activated carbon from agricultural waste materials (palm oil shells, coconut shells, rice husks) represents an opportunity to reduce costs and develop sustainable, locally-appropriate treatment solutions, though ensuring consistent quality and regeneration capacity requires further development [1].

Constructed wetlands and nature-based treatment systems offer particular promise for the Indonesian context given the favorable tropical climate, availability of land in some regions, lower capital and operating costs compared to engineered systems, and multiple co-benefits including habitat creation and aesthetic improvements [4]. These systems achieve emerging contaminant removal through multiple mechanisms including biodegradation by diverse microbial communities, plant uptake and transformation, photodegradation under tropical sunlight, and sorption to sediments and plant materials. While removal efficiencies for specific emerging contaminants vary depending on compound properties and system design, constructed wetlands represent a cost-effective option particularly suitable for small communities, institutional facilities, and decentralized treatment applications [5]. Expanding research and demonstration projects on optimized constructed wetland designs for Indonesian conditions—considering factors such as tropical plant selection, monsoon hydrology, and maintenance requirements—could support wider adoption of this promising treatment approach. Figure 2 presents a comparative assessment of these treatment technologies, evaluating their emerging contaminant removal efficiency, cost-effectiveness, and implementation feasibility specific to Indonesian contexts.

4.4 Remediation Initiatives and Management Programs

Recognizing the severity of water pollution in critical hotspots, the Indonesian government has launched several high-profile remediation initiatives aimed at restoring degraded aquatic ecosystems and improving water quality [13]. The Citarum Harum ("Fragrant Citarum") program, initiated in 2018, represents the most ambitious and visible of these efforts, deploying a whole-of-government approach backed by presidential authority to address pollution in the Citarum River Basin [13, 14]. The program involves military personnel in waste removal and monitoring activities, coordinates multiple government agencies in enforcement and infrastructure development, engages local communities in behavior change campaigns, and seeks to hold industries accountable for pollution control compliance.

Initial phases of Citarum Harum achieved notable progress in removing accumulated solid waste from river channels and banks, relocating informal settlements from riparian areas, closing or relocating non-compliant small industries, and improving waste collection services in previously underserved areas. However, fundamental challenges persist regarding the sustainability of improvements and achievement of ultimate water quality restoration goals. Industrial compliance remains problematic, particularly for the thousands of small and medium enterprises that may lack financial resources or technical capacity to install adequate wastewater treatment systems even when regulatory pressure increases. The program's reliance on military presence for enforcement raises questions about sustainability once military deployment concludes, while the political and financial commitment required to construct sufficient wastewater treatment infrastructure to serve the basin's 15 million inhabitants far exceeds resources allocated to date [13].

Beyond Citarum Harum, Indonesia has designated certain other polluted rivers and lakes for restoration efforts, though generally with less intensive interventions and resources than mobilized for the Citarum. The National Movement to Save Indonesian Lakes identifies priority lake systems facing eutrophication, sedimentation, and pollution threats, with Lake Rawapening among those designated for restoration action [45]. However, translating designation into effective restoration requires sustained funding, technical capacity, stakeholder coordination, and political will that often prove challenging to maintain over the multi-year to multi-decade timescales required for ecosystem recovery.

Public-private partnerships and corporate social responsibility initiatives represent another avenue for pollution control action, with some major industries investing in improved wastewater treatment, cleaner production processes, and community engagement programs. Industry associations in sectors such as textiles and food processing have developed guidelines and provided training on pollution prevention and treatment technologies, though actual implementation varies widely among member companies. Community-based river care groups (Komunitas Peduli Sungai) have emerged in various cities, conducting monitoring, raising public awareness, advocating for policy action, and sometimes implementing small-scale cleanup and restoration activities. While these grassroots efforts generate valuable social capital and can catalyze broader action, they typically lack resources and authority to address the industrial and infrastructure investments required for fundamental water quality improvements [13].

International cooperation provides important support for Indonesia's water pollution management efforts through financial assistance, technology transfer, and capacity building. The World Bank, Asian Development Bank, and bilateral partners including Japan, Netherlands, Germany, and others have supported wastewater treatment infrastructure development, river basin management planning, and institutional capacity strengthening. These international partnerships have introduced advanced technologies, supported policy development, and financed major infrastructure investments that would otherwise be unaffordable. However, ensuring that international assistance translates into sustainable, locally-owned programs rather than donor-driven projects

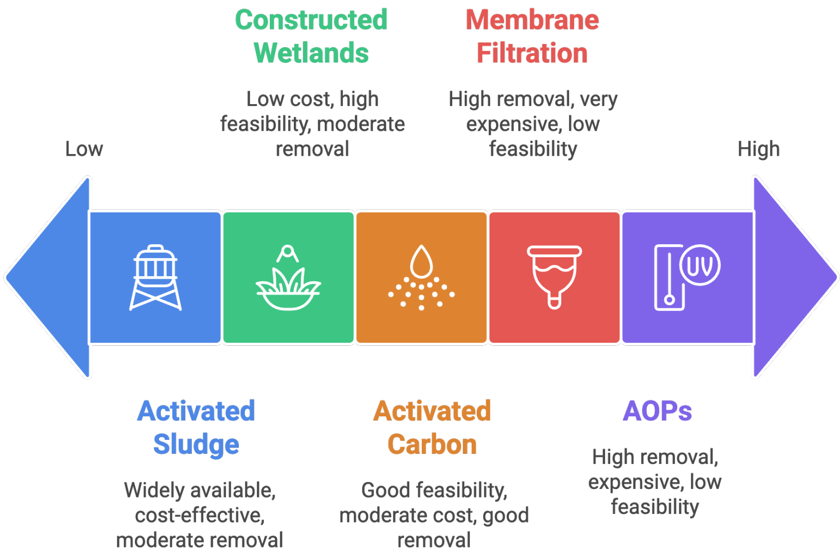


Figure 2. Comparative assessment of wastewater treatment technologies for emerging contaminant removal in Indonesia. Five approaches are evaluated by removal efficiency, cost-effectiveness, and implementation feasibility. Constructed wetlands and activated carbon offer promising options for tropical, decentralized contexts.

that struggle after external funding concludes remains an ongoing challenge requiring careful attention to institutional development, local capacity building, and financial sustainability mechanisms [1].

5. CRITICAL KNOWLEDGE GAPS AND RESEARCH PRIORITIES

Despite the expanding body of research documenting emerging contaminant occurrence in Indonesian aquatic environments, substantial knowledge gaps persist that hinder comprehensive understanding of contamination patterns, ecological and health risks, and optimal management strategies. These gaps reflect both the relative novelty of emerging contaminant research in Indonesia—with systematic investigations intensifying only within the past decade—and the inherent complexities of studying diverse chemicals at trace concentrations in heterogeneous tropical environments. Addressing these knowledge gaps through targeted research represents a critical priority for developing evidence-based policies, designing effective treatment interventions, and protecting Indonesia's valuable aquatic resources and the millions who depend upon them. Figure 3 presents a priority matrix mapping critical research needs against current data availability, identifying areas requiring immediate research attention to enable effective management.

Figure 3. Priority matrix of research gaps and data availability for emerging contaminants in Indonesia. Four quadrants: (1) Critical Research Gaps—high priority, low data; (2) Immediate Action Areas—high priority, sufficient data; (3) Emerging Concerns—lower priority, low data; (4) Well-Characterized Issues—lower priority, sufficient data. Bubble size indicates relative importance.

Spatial and temporal data gaps constitute perhaps the most fundamental limitation in current understanding. The geographic concentration of emerging contaminant studies in Java, particularly in the Citarum River Basin and Jakarta metropolitan area, creates a substantial knowledge imbalance whereby contamination patterns in Sumatra, Kalimantan, Sulawesi, and eastern Indonesia remain largely uncharacterized [6, 7]. While Java's exceptional population density and industrial concentration justify focused research attention, the absence of systematic surveillance in other islands prevents comprehensive national assessment and risks overlooking significant contamination that may be occurring in understudied regions experiencing rapid industrialization, agricultural intensification, or resource extraction [1]. Furthermore, most existing studies represent single sampling campaigns or short-duration investigations rather than long-term monitoring programs capable of detecting temporal trends, assessing seasonal variations, or evaluating effectiveness of management interventions [13, 14]. The pronounced wet and dry seasons characteristic of Indonesia's tropical climate likely generate substantial temporal variation in emerging contaminant concentrations as monsoon rainfall mobilizes accumulated pollutants and influences dilution factors, yet systematic studies examining these seasonal dynamics remain limited [19].

Ecotoxicological knowledge gaps represent another critical research priority, as the vast majority of toxicity data informing risk assessments derive from studies conducted on temperate-region model organisms rather than tropical species native to Indonesian aquatic ecosystems [4, 5]. Extrapolating effect thresholds from temperate fish, invertebrates, and algae to tropical species involves substantial uncertainty, as thermal physiology, metabolic rates, and toxicant sensitivity may differ significantly between organisms adapted to different thermal environments [6]. Indonesia's exceptional aquatic biodiversity—including numerous endemic species found nowhere else—creates particular concern, as the sensitivity of these evolutionarily unique organisms to emerging contaminant exposure remains essentially unknown despite their conservation importance [9]. Mixture toxicity represents another poorly characterized dimension, as real-world contamination involves simultaneous exposure to dozens or hundreds of chemicals that may interact synergistically, additively, or antagonistically to produce effects different from those predicted based on individual compound toxicity [16, 8]. Understanding chronic low-dose exposure effects, sublethal impacts on reproduction and behavior, and multigenerational consequences requires long-term laboratory and field studies that remain scarce in the Indonesian research literature [1].

The fate and transport of emerging contaminants in tropical aquatic environments warrant substantially greater research attention, as environmental processes governing contaminant persistence, transformation, and bioavailability may differ markedly from temperate systems where most mechanistic studies have been conducted [4]. High solar radiation characteristic of tropical latitudes may enhance photodegradation of certain compounds, while elevated water temperatures could accelerate biodegradation and chemical hydrolysis but also influence sorption equilibria and volatilization rates in ways that require empirical characterization for Indonesian conditions [6, 5]. The intense rainfall and flooding associated with monsoon seasons represent particularly important but understudied processes that mobilize contaminants from terrestrial sources, resuspend contaminated sediments, and potentially facilitate long-distance transport during extreme events [19, 11]. Climate change adds additional complexity and urgency, as altered precipitation patterns, rising temperatures, sea-level rise affecting coastal contamination dynamics, and increasing frequency of extreme weather events will likely influence emerging contaminant fate and exposure pathways in ways that remain poorly quantified [4, 8].

Finally, research translating into practical, context-appropriate solutions represents a critical need. While advanced treatment technologies exist that can effectively remove emerging contaminants, their high capital and operating costs, energy requirements, and technical complexity often exceed the resources and capabilities of Indonesian municipalities and industries [1, 29]. Research developing and demonstrating cost-effective, locally-appropriate technologies—including nature-based treatment systems optimized for tropical conditions, locally-produced activated carbons from agricultural wastes, low-cost passive samplers for monitoring, and community-managed decentralized treatment—could provide viable pathways for expanding emerging contaminant management where conventional high-technology solutions remain inaccessible [5, 16]. Integrating traditional ecological knowledge with modern science, engaging communities in monitoring and management, and designing interventions that account for Indonesia's specific socioeconomic, institutional, and environmental contexts will be essential for translating research findings into real-world pollution reduction.

6. FUTURE PERSPECTIVES AND POLICY RECOMMENDATIONS

Addressing the multifaceted challenge of emerging contaminant pollution in Indonesian aquatic environments requires coordinated action across multiple domains—regulatory development, monitoring infrastructure enhancement, treatment technology deployment, research capacity building, and stakeholder engagement. While the magnitude of the challenge is substantial, Indonesia possesses significant assets including growing scientific capacity, increasing environmental awareness, political commitment demonstrated through initiatives like Citarum Harum, and opportunities to learn from international experiences while developing context-appropriate solutions suited to Indonesia's specific environmental, economic, and social conditions. This section presents forward-looking perspectives and actionable recommendations organized around key intervention domains, emphasizing practical pathways for progress that balance ideal objectives against resource constraints and institutional realities. Figure 4 illustrates an integrated management framework that coordinates these multiple intervention domains in a coherent, mutually reinforcing approach.

6.1 Strengthening Regulatory Frameworks

Developing comprehensive regulatory frameworks that explicitly address emerging contaminants represents a foundational priority for advancing pollution control in Indonesia [1, 6]. A phased, risk-based approach offers the most practical pathway forward, beginning with priority substances where contamination is well-documented, toxicological data are relatively robust, and analytical methods are established. Antibiotics represent strong candidates for initial regulatory attention given extensive documentation of contamination across Indonesian waters, clear concerns regarding antimicrobial resistance development, and existence of international precedents for pharmaceutical regulation that can inform Indonesian standard-setting [13, 14]. Similarly, certain widely-detected pesticides and industrial chemicals could be incorporated into water quality standards through amendments to existing regulations, building incrementally on the established regulatory structure rather than requiring entirely new frameworks [42].

PFAS regulation merits particular attention given the persistence and bioaccumulation characteristics of these compounds, documented contamination in Indonesian environmental matrices and human tissues, and rapid evolution of international regulatory standards that Indonesia could leverage [39]. Many jurisdictions have recently adopted or strengthened PFAS drinking water standards, providing regulatory precedents and scientific assessments that could inform Indonesian standard development. Establishing maximum contaminant levels for priority PFAS compounds in drinking water, followed by surface water quality criteria and eventually wastewater discharge limits, would represent a logical progression aligned with international trends and precautionary protection of public health [4].

Microplastics present unique regulatory challenges given their physical rather than chemical nature, diversity of polymer types and particle characteristics, and absence of broadly accepted concentration metrics or effect thresholds. Rather than conventional maximum contaminant level approaches,

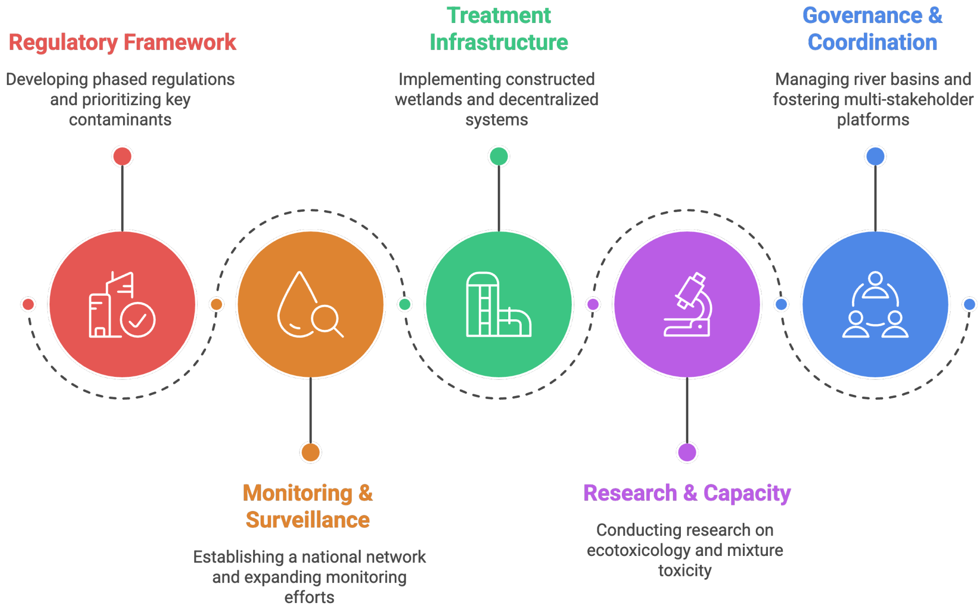


Figure 4. Integrated management framework for emerging contaminants in Indonesia. Five interconnected domains: regulatory development, monitoring and surveillance, treatment infrastructure, research and capacity building, and governance and coordination. Arrows indicate adaptive, cyclical information flow between components.

microplastic management may be better addressed through source control measures—including single-use plastic reduction policies, improved solid waste management, wastewater treatment requirements specifically targeting microplastic removal, and extended producer responsibility schemes that internalize plastic pollution costs [7, 8]. Indonesia's existing national action plan for marine plastic debris provides a foundation that could be expanded to more comprehensively address microplastics across all aquatic environments.

Beyond specific contaminant regulations, strengthening the overall water quality management framework requires enhanced monitoring requirements that mandate emerging contaminant surveillance in priority water bodies, improved wastewater discharge permitting that establishes facility-specific limits based on receiving water sensitivity and treatment capability, and strengthened enforcement mechanisms with meaningful penalties for non-compliance [13]. Regional approaches that harmonize regulations across ASEAN member states could facilitate trade while preventing regulatory arbitrage whereby industries relocate to countries with weaker environmental standards, creating a "race to the bottom" harmful to all nations in the region [6].

6.2 Expanding Monitoring Capacity and Data Systems

Systematic, sustained monitoring represents an essential foundation for understanding contamination trends, assessing management effectiveness, and informing evidence-based policy decisions [1]. Establishing a national emerging contaminant monitoring program, implemented through coordination between the Ministry of Environment and Forestry, Ministry of Health, and provincial environmental agencies, would provide the data infrastructure needed to support regulatory development and track progress toward water quality objectives. A tiered monitoring design could balance comprehensive coverage against resource constraints by establishing intensive monitoring sites in priority hotspots supplemented by less frequent surveillance across broader geographic areas, with site selection guided by population density, industrial activity, ecological sensitivity, and existing data gaps [6, 7].

Priority should be given to expanding monitoring capacity beyond Java to systematically characterize contamination in Sumatra, Kalimantan, Sulawesi, and eastern Indonesia, where rapid development likely generates significant emerging contaminant pollution that remains poorly documented [1]. Mobile laboratories and regional analytical hubs could help overcome geographic disparities in laboratory capacity, while partnerships with university research facilities can leverage existing equipment and expertise to expand analytical capacity without requiring complete duplication of infrastructure [7].

Passive sampling technologies offer promising opportunities for cost-effective monitoring that integrates contaminant concentrations over time, smoothing temporal variability and providing exposure metrics more relevant to chronic effects than discrete grab samples [4]. Development and validation of locally-produced passive samplers using readily available materials could dramatically expand monitoring capacity while building local technical expertise. Similarly, effect-based monitoring approaches—using bioassays that detect biological activity such as estrogenicity, mutagenicity, or antimicrobial resistance rather than quantifying individual chemicals—can provide integrated assessments of mixture toxicity and identify emerging concerns not captured by targeted chemical analysis [5, 8].

Establishing robust data management systems that ensure quality-assured data are publicly accessible through online portals would enhance transparency, facilitate research, enable public engagement, and support accountability. Learning from international programs such as the U.S. National Water Quality Monitoring Network or European Water Information System, Indonesia could develop data infrastructure that makes monitoring results readily available to researchers, policymakers, industries, civil society organizations, and concerned citizens [6]. Open data policies combined with capacity building for data analysis and interpretation would maximize the value of monitoring investments and catalyze broader engagement in water quality protection.

6.3 Advancing Treatment Technologies and Infrastructure

Expanding wastewater treatment infrastructure represents perhaps the single most impactful intervention for reducing emerging contaminant loads entering Indonesian aquatic environments, given that the vast majority of domestic and much industrial wastewater currently receives no treatment before discharge [1, 3]. However, the capital investments required to construct conventional centralized wastewater treatment systems serving Indonesia's hundreds of millions of urban and peri-urban residents far exceed available public resources, necessitating creative approaches that combine different treatment paradigms suited to specific contexts [5].

Decentralized and nature-based treatment solutions offer particular promise for rapidly expanding treatment coverage at lower cost than conventional centralized infrastructure. Constructed wetlands, stabilization ponds, and community-scale treatment systems can achieve substantial pollutant removal—including meaningful reduction of many emerging contaminants—with lower capital and operating costs, simpler operation and maintenance, and better alignment with Indonesia's institutional and financial realities [4, 16]. Developing Indonesian design standards for tropical constructed wetlands, demonstrating performance through pilot installations, training local operators, and establishing financing mechanisms could catalyze widespread adoption. Indonesia's favorable climate, availability of land in many contexts, and traditions of community management create conducive conditions for nature-based treatment expansion [5].

For existing centralized treatment plants, cost-effective upgrade pathways should be identified and demonstrated. Powdered activated carbon addition to conventional activated sludge systems represents a relatively accessible option for enhancing removal of dissolved organic micropollutants without requiring fundamental process redesign [16]. Using locally-produced activated carbon from agricultural wastes (oil palm shells, coconut shells, rice husks) could reduce costs while supporting circular economy principles, though quality assurance and regeneration capacity require development [1]. Advanced oxidation processes, while more complex and energy-intensive, may be justified for specific high-priority applications such as hospital wastewater treatment where pharmaceutical loads are concentrated and antimicrobial resistance concerns are acute [29].

Industrial wastewater treatment requirements should emphasize source reduction and cleaner production as first priorities, followed by sector-specific treatment technologies appropriate to characteristic contaminants. The textile industry, given its massive scale in Indonesia and severe pollution potential, merits focused attention through development of best available technology guidelines, demonstration of cost-effective treatment approaches, and financial/technical assistance programs that help small and medium enterprises achieve compliance [38]. Extended producer responsibility policies could shift treatment costs to manufacturers whose products generate downstream pollution, creating economic incentives for designing less-polluting products and processes [8].

6.4 Research Priorities and Capacity Development

Strategic research investments should target knowledge gaps that most constrain effective management, with particular emphasis on questions specific to Indonesian environmental conditions, organisms, and contexts where extrapolation from temperate-region studies is inadequate [4, 6]. Ecotoxicological studies using tropical fish, invertebrate, and algal species—particularly endemic taxa of conservation concern—would generate locally-relevant effect thresholds to replace reliance on temperate model organisms and enable more confident risk assessments [9]. Understanding mixture toxicity under realistic environmental exposure scenarios, chronic low-dose effects, and multi-generational impacts requires long-term studies that balance ecological relevance against experimental tractability [1, 8].

Fate and transport research should examine how tropical conditions—elevated temperatures, intense solar radiation, monsoon hydrology, and climate change impacts—influence contaminant persistence, transformation, and bioavailability in Indonesian aquatic systems [5, 19]. Field studies coupling detailed hydrological characterization with contaminant monitoring during monsoon events could elucidate mobilization and transport processes, while climate change scenario modeling would help anticipate how shifting precipitation patterns and rising temperatures may alter exposure pathways [4].

Source apportionment studies using chemical fingerprinting, statistical modeling, and targeted sampling can identify major contributors to contamination, enabling interventions to be focused where they will achieve greatest impact [15]. Understanding relative contributions from domestic wastewater, industry, agriculture, and other sources for specific contaminants in particular water bodies guides prioritization of management actions—for instance, whether pharmaceutical contamination control should emphasize proper disposal programs for unused medicines, hospital wastewater treatment, or municipal treatment plant upgrades [13].

Capacity building represents an equally critical investment, encompassing analytical chemistry training for laboratory personnel, environmental engineering education emphasizing emerging contaminants for the next generation of practitioners, and continuing education for government regulators and enforcement staff [1]. Partnerships between Indonesian universities and international institutions can facilitate knowledge transfer, while South-South cooperation with other tropical developing nations facing similar challenges may yield particularly relevant insights and foster collaborative research addressing shared concerns [6].

6.5 Improving Governance and Multi-Stakeholder Collaboration

Effective water quality management transcends technical and scientific dimensions to fundamentally depend on governance quality, institutional coordination, stakeholder engagement, and political will [13]. Indonesia's complex multi-level governance structure—with water quality responsibilities distributed across national ministries, provincial governments, and district/municipal authorities—creates coordination challenges that require clear delineation of roles, improved inter-agency communication, and collaborative planning processes that align actions across administrative levels and sectoral domains [1].

River basin management approaches that organize governance around hydrological rather than administrative boundaries offer promise for integrated pollution control, as demonstrated by various international examples [6]. Strengthening Indonesia's river basin organizations (Balai Besar Wilayah Sungai) with adequate authority, technical capacity, and financial resources to coordinate pollution control across jurisdictions within their basins could improve coherence and effectiveness of management actions. Multi-stakeholder platforms that engage government agencies, industries, civil society organizations, academic institutions, and local communities in collaborative planning and monitoring create ownership and leverage diverse capabilities [13].

Public awareness and behavior change represent essential components of pollution control, as individual decisions regarding medication disposal, plastic consumption, pesticide application, and waste management collectively determine environmental contamination loads. Strategic communication campaigns that build understanding of emerging contaminant issues, communicate protective behaviors, and foster environmental stewardship can complement regulatory and technological interventions [7]. Community-based monitoring programs that train and equip local groups to conduct water quality surveillance generate valuable data while building engaged constituencies that advocate for pollution control [13].

Corporate environmental responsibility must evolve beyond voluntary initiatives to become embedded in core business operations through regulatory requirements, market incentives, and social license expectations. Mandatory environmental performance disclosure, integration of water pollution impacts into corporate sustainability reporting, preferential procurement policies favoring environmentally responsible suppliers, and green finance mechanisms that channel investment toward clean production can create business cases for pollution prevention [6, 8].

International cooperation will remain important for Indonesia's emerging contaminant management, providing financial resources, technology transfer, capacity building, and opportunities to learn from global experiences while contributing to international knowledge through Indonesia's unique perspectives as a megadiverse tropical archipelagic nation. Engaging constructively in regional forums such as ASEAN environmental cooperation, participating in international scientific assessments, and advocating for global action on transboundary pollutants like PFAS and plastic pollution positions Indonesia as both recipient and contributor in the global community addressing shared environmental challenges [6].

7. CONCLUSIONS

This review demonstrates that emerging contaminants—including pharmaceuticals, microplastics, PFAS, pesticides, and endocrine-disrupting chemicals—are pervasive in Indonesian aquatic environments, with particularly severe contamination documented in Java's industrialized river basins and coastal zones. The Citarum River Basin and Jakarta Bay exemplify pollution hotspots where pharmaceutical loads reach hundreds of tons annually, microplastic abundances rank among the world's highest, and complex industrial chemical mixtures create fundamentally altered ecosystems. However, limited research outside Java obscures the true national scope of contamination, with rapid industrialization across Sumatra, Kalimantan, Sulawesi, and eastern Indonesia likely generating comparable pollution that remains poorly characterized.

Indonesia's regulatory and management framework faces critical gaps. Government Regulation No. 22 of 2021, designed primarily for conventional pollutants, lacks specific standards for most emerging contaminants [1, 13]. Wastewater treatment infrastructure serves less than 10% of the population, with conventional technologies achieving incomplete removal of trace organic contaminants [1, 3]. Monitoring capacity remains constrained by limited analytical infrastructure concentrated in Java, insufficient financial resources for systematic surveillance, and weak enforcement mechanisms despite documented contamination and recognized health and ecological risks.

Despite these challenges, encouraging developments provide pathways forward. The Citarum Harum program demonstrates political commitment to water quality restoration, while Indonesia's growing research community generates increasingly sophisticated contamination assessments and management evaluations. Technological advances offer context-appropriate solutions: nature-based treatment systems suited to tropical conditions, locally-produced activated carbon from agricultural wastes, and cost-effective monitoring approaches can expand capacity while supporting circular economy principles [5, 4, 16]. International cooperation provides essential financial resources, technology transfer, and capacity building that accelerate implementation of advanced approaches.

Effective management requires integrated action across multiple domains. Priority interventions include: (1) phased regulatory development beginning with well-documented priority substances such as antibiotics and PFAS; (2) establishment of national monitoring programs with strategic geographic coverage balancing intensity against resource constraints; (3) accelerated wastewater treatment infrastructure deployment emphasizing decentralized and nature-based solutions where appropriate; (4) targeted research addressing tropical-specific fate and effects, mixture toxicity, and locally-relevant exposure pathways; and (5) strengthened governance through improved inter-agency coordination, multi-stakeholder engagement, and evidence-based policymaking. Successfully addressing emerging contaminant pollution is essential for protecting Indonesia's exceptional aquatic biodiversity, safeguarding fisheries that provide protein to hundreds of millions, and achieving Sustainable Development Goals related to water, health, and environmental sustainability.

Indonesia stands at a critical juncture where near-term decisions will shape water quality trajectories for decades. Continued economic development without proactive pollution prevention risks intensifying contamination, while strategic investments in regulatory frameworks, treatment infrastructure, monitoring capacity, and research can fundamentally alter this trajectory. With coordinated efforts across government, industry, academia, and civil society—guided by sound science, informed by international best practices while grounded in Indonesian realities, and sustained through long-term commitment—Indonesia can develop robust frameworks for managing emerging contaminants that protect both environmental and human health for current and future generations.

DATA AVAILABILITY STATEMENT

Data available on request from the corresponding author.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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