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Review

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Bridging Recreational Planning and Environmental Contamination: A Critical Evidence Review of Sources, Exposure Pathways and Planning Implications

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How To Cite: Jacob, D.E.; Jacob, I.D. Bridging Recreational Planning and Environmental Contamination: A Critical Evidence Review of Sources, Exposure Pathways and Planning Implications. *Environmental Contamination: Causes and Solutions* **2026**, *2*(2), 9. https://doi.org/10.53941/eccs.2026.100009

Received: 22 September 2026
Revised: 11 November 2026
Accepted: 20 November 2026
Published: 26 November 2026

Abstract: Recreational beaches, lakes, rivers and swimming facilities are simultaneously ecological systems, public spaces and environments of direct human contact. Their sustainability depends not only on accessibility and visitor capacity but also on effective environmental contamination management. This review examines evidence of contamination in recreational environments, focusing on contaminant sources, environmental distribution, potential exposure pathways and implications for recreational planning. The synthesis covers 21 primary empirical studies reporting microplastics and plastic debris, microbial indicators, pesticides, potentially toxic elements, petroleum hydrocarbons, persistent organic pollutants, phthalates and personal-care product residues. The studies varied considerably in geographical coverage, sampling designs, environmental matrices, analytical methods and reporting units; therefore, quantitative findings were reported at study level rather than pooled. Reported microplastic concentrations included 106.50 ± 34.41 items/kg in Haichow Bay beach sediment, 98.17 ± 12.85 items/m^3 in Nikli Lake water and 109.67 ± 10.89 items/kg in its dry sediment. Lake Hazar surface-water concentrations ranged from 74 to 1091 items/m^3. In the Salt River, concentrations increased from 27,798 MPs/m^3 in the morning to 222,391 MPs/m^3 during peak recreational activity. Microplastics were detected in the gastrointestinal tracts of 28 of 80 examined fish (35% occurrence), although this does not establish human exposure through consumption. Other studies documented microbial and chemical contamination. Most studies assessed environmental occurrence rather than human health outcomes or the effectiveness of planning interventions. The review highlights source control, catchment-based planning, sanitation, waste infrastructure, spatial zoning and adaptive monitoring as important responses. It also identifies the need for standardised, geographically broader research to strengthen evidence-based recreational planning.

Keywords: recreational planning; environmental contamination; recreational water; microplastics; beach management; lakes; tourism; source control; adaptive monitoring

1. Introduction

Recreational environments occupy a distinctive position in environmental management because they function simultaneously as ecological systems, public spaces, locations of economic activity and settings where people may come into contact with environmental contaminants [1,2]. Beaches, lakes, rivers, waterfronts and swimming

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facilities support exercise, leisure, tourism, social interaction and psychological restoration [3]. However, the environmental qualities that attract visitors can also be placed under pressure by recreational activities and surrounding land uses, Visitor concentration can increase litter and material inputs; bathing can disturb sediments; boating and fishing can introduce or redistribute plastics; and high-use waterfronts can intersect with stormwater, wastewater and urban drainage [4,5]. At the same time, contamination can arrive from well beyond the recreational boundary through agricultural runoff, urban land use, industrial discharge, sewage and hydrological transport [6,7]. Consequently, environmental contamination is not simply a water-quality or waste-management concern; it is also a spatial-planning and environmental-governance issue. The World Health Organization's recreational-water guidance emphasises preventive risk management, surveillance and site-specific water safety planning [8]. This supports the integration of environmental quality considerations into recreational planning before facilities are developed or recreational activities intensify, rather than relying exclusively on corrective action after contamination has occurred.

The literature nevertheless remains fragmented. Environmental contamination studies commonly treat beaches, lakes or rivers as sampling locations, while recreational-planning studies more often emphasise accessibility, carrying capacity, landscape design, tourism development and user experience. This separation limits understanding of how recreational development, infrastructure placement and visitor-management decisions may influence contaminant generation, distribution and opportunities for human contact. A beach concession can change waste flows; the location of a stormwater outlet can determine where runoff reaches swimmers; the spatial arrangement of fishing and swimming zones can alter contact with contaminated sediment; and the timing of large recreational events can change contaminant concentrations over hours rather than days. Evidence from Haichow Bay links higher microplastic abundance with resort beaches and tourism intensity [9], while evidence from the Salt River shows a pronounced temporal increase in microplastics during recreational use [4]. These findings suggest that recreational activities may influence contamination patterns under particular environmental and management conditions. Nevertheless, observed associations should not automatically be interpreted as proof that visitor activity alone caused the contamination, because upstream inputs, hydrological conditions and other sources may also contribute. Recreation should therefore be understood both as an activity that may be affected by environmental contamination and as a potential influence on the environmental conditions of recreational sites.

Microplastics provide a particularly useful lens through which to examine this relationship because they are persistent, mobile, difficult to remove after dispersion and capable of occurring simultaneously in water, sediments and organisms [10,11]. Weathering processes, including ultraviolet radiation, photo-oxidation and mechanical abrasion, can weaken larger plastic materials and fragment them into smaller particles. However, physical fragmentation should not be confused with chemical depolymerisation, which involves the breakdown of polymer chains into smaller chemical compounds or their constituent monomers. The extent and rate of these processes depend on polymer composition and environmental conditions, and complete depolymerisation is generally not expected under ordinary aquatic conditions [12,13]. Different plastic polymers also have different constituent monomers. For example, polyethylene terephthalate (PET) is produced from ethylene glycol and terephthalic acid, whereas styrene and vinyl chloride are the respective monomers of polystyrene and polyvinyl chloride. Phthalate esters (PAEs), however, are not PET degradation products; they are separate chemical compounds commonly used as plasticising additives in certain plastic materials. Similarly, bisphenol A (BPA) is associated with the manufacture of polycarbonate plastics and epoxy resins. These additives and associated chemicals may enter the environment through migration or leaching, although their release and potential effects depend on the specific chemical, plastic formulation and environmental conditions. The planning implications nevertheless extend beyond plastics. Recreational waters can carry faecal organisms and waterborne pathogens [3,14]; pesticides can enter lakes from urban and agricultural catchments [6]; potentially toxic elements can accumulate in recreational lakes [15,16]; petroleum hydrocarbons can contaminate water, sediment and fish [17]; and plastic-associated chemicals and personal-care compounds are increasingly detectable in recreational waters [18,19]. Each pathway demands a different planning response, including waste prevention, wastewater control, catchment land-use management and targeted environmental assessment [20,21]. Importantly, environmental detection does not automatically establish human exposure or health risk.

This review addresses that gap by critically synthesising empirical evidence on contamination in recreational environments and examining how the observed sources, pathways, spatial patterns and temporal dynamics can inform recreational planning. Four linked questions guide the synthesis: what contaminants have been measured in recreational environments; what quantitative patterns and potential exposure indicators have been reported; how do catchment processes and recreational activities interact with contamination; and what planning responses are supported by the evidence? The review is intentionally analytical rather than purely descriptive. Numerical results are retained at study level and are not pooled when matrices, units or analytical approaches are incompatible [22,23].

This distinction is essential because an abundance reported as items per cubic metre cannot be directly combined with items per kilogram of sediment, just as microbial counts cannot be treated as equivalent to chemical concentrations. Similarly, microplastic detection in fish does not independently demonstrate human exposure through consumption. Since most available studies measure environmental occurrence rather than evaluate planning interventions, recommendations are interpreted as evidence-informed planning implications rather than proven intervention effects. The objective is therefore to identify robust cross-study patterns while preserving the context in which individual measurements were generated.

2. Methods

2.1. Review Design and Reporting Approach

This review adopted a PRISMA 2020-informed critical evidence synthesis approach [24]. Systematic literature searches were conducted in the Web of Science Core Collection, Scopus, PubMed/MEDLINE, and ScienceDirect between 18 July and 9 August 2026. The search strategy used Boolean operators (AND, OR) to combine two core concept groups: recreational environments and environmental contamination.

The recreational environment concept incorporated terms including:

("recreational beach" OR "recreational lake" OR "recreational river" OR "swimming pool" OR "splash pad" OR "tourism" OR "recreation" OR "waterfront recreation" OR "coastal recreation")

The environmental contamination concept incorporated:

("microplastics" OR "plastics" OR "marine litter" OR "microbial contamination" OR "bacteria" OR "water quality" OR "sewage" OR "wastewater" OR "runoff" OR "pesticides" OR "heavy metals" OR "hydrocarbons" OR "persistent organic pollutants" OR "phthalates" OR "personal-care products")

The evidence base comprised peer reviewed empirical studies together with selected authoritative public health sources whose findings or recommendations directly informed the assessment of contamination prevention, exposure reduction or environmental management in recreational settings. The review considered literature published between January 2010 and August 2026. Publications from 2026 were retained only where they formed part of the established evidence extraction set and their publication details could be independently verified. The review was designed as a critical evidence synthesis rather than a quantitative meta-analysis, allowing findings from different contaminant categories, environmental settings and methodological approaches to be examined comparatively.

2.2. Search Strategy and Eligibility

Studies were considered eligible when they investigated contamination in recreational environments directly used by people, quantified environmental contamination or documented a clearly defined contamination pathway, and provided sufficient methodological information to permit interpretation of their findings. Studies examining management or planning interventions directly relevant to recreational environmental quality were also considered. Authoritative public health sources were selectively included where they provided relevant guidance on recreational water safety, contamination prevention or environmental management. These sources informed the contextual and management interpretation of the findings but were not classified as primary empirical studies. Studies were excluded when they focused exclusively on non-recreational industrial sites or offshore deep-sea environments; employed laboratory-based mesocosm systems without an identifiable real-world recreational context; were editorials, commentaries, conference abstracts or non-empirical literature reviews; or provided neither quantifiable contamination measures nor sufficiently clear evidence of a contamination pathway relevant to recreational environments.

Study identification and selection were informed by the principal stages of the PRISMA 2020 framework [24], comprising literature identification, title and abstract assessment, full-text eligibility assessment and inclusion in the final evidence synthesis (Figure 1). The selection process applied the stated eligibility and exclusion criteria to determine the relevance of retrieved publications to the review objectives. However, the original database export files, deduplication records and stage-by-stage screening logs were unavailable for independent verification. Consequently, the exact number of records retrieved from individual databases, duplicates removed, records excluded during screening and full-text reports excluded could not be reliably established. These numerical screening details are therefore not reported to avoid presenting unverified figures as observed results.

The final analytical evidence base comprised 21 primary empirical studies addressing contamination in recreational environments, contamination sources, environmental distribution and potential exposure pathways. Selected authoritative public health sources provided additional context for interpreting contamination risks and management implications but were considered separately from the empirical evidence base. The included studies were examined through qualitative thematic synthesis, with attention to contaminant categories, environmental

settings, sampling approaches, reported contamination levels and implications for recreational planning and environmental management.

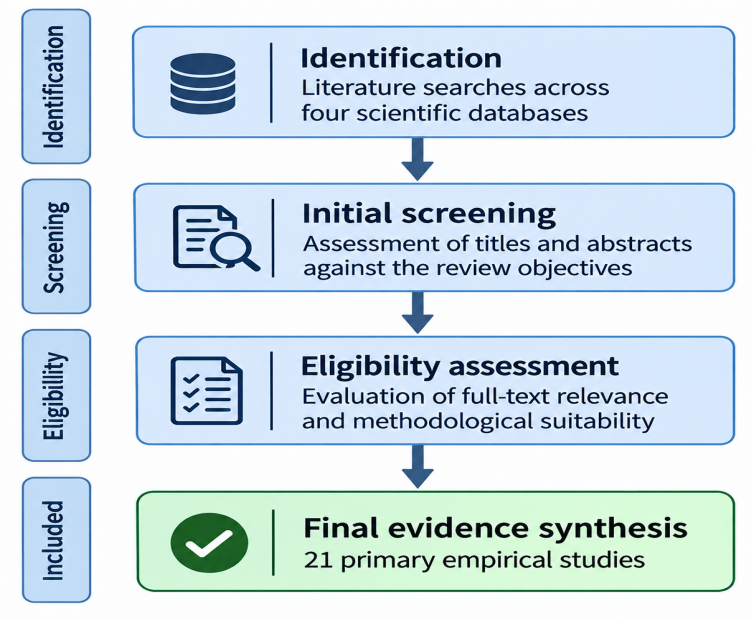


Figure 1. PRISMA flow diagram for study selection.

2.3. Data Extraction and Analytical Synthesis

Data were extracted according to four analytical dimensions: source, pathway, recreational activity, and planning response. The extraction framework recorded geographical location, recreational setting, environmental matrix, contaminant type, sample characteristics, analytical method, principal quantitative finding, spatial or temporal pattern, source attribution, and management implication. Quantitative results were retained in their original published form. Where reported, means were retained with their standard deviations, ranges were retained as ranges, and biological occurrence was recorded using the original numerator and denominator. No pooled concentration estimates were calculated across incompatible environmental matrices, consistent with guidance for synthesis without meta analysis (SWiM) [22].

This approach distinguishes recurrence of contamination from direct numerical comparability. Such distinction is particularly important for microplastics because studies differ substantially in particle size thresholds, extraction procedures, polymer confirmation techniques, and reporting units [25,26]. Consequently, a higher reported concentration in one study cannot automatically be interpreted as indicating greater environmental or health risk than a lower concentration reported from another environmental matrix using a different analytical protocol. The synthesis was organized into five evidence domains: plastics and microplastics; microbial and sewage associated contamination; agricultural, urban, and chemical contamination; recreational activity and exposure; and planning and management interventions. This structure enables the review to progress from contamination measurement to potential mechanisms and subsequently to planning and management responses. It also avoids treating individual contaminants as isolated issues, consistent with the principles of narrative synthesis [23]. The principal unit of interpretation was the recreational system, defined by the interaction among the recreational activity areas, surrounding catchment, material and wastewater pathways, environmental compartments, and responsible management and regulatory institutions. No formal risk-of-bias or study-quality scoring was documented in the original review process; accordingly, the studies were not assigned comparative quality scores or weighted as though their designs provided equivalent levels of evidence.

3. Results

3.1. Geographical Distribution and Composition of the Evidence Base

The synthesized evidence base comprises 21 primary empirical studies published between 2010 and 2026. The studies were distributed across 11 countries, with the United States contributing the largest number (seven studies; 33.3%). India, Malaysia, Nigeria, and South Korea contributed two studies each (9.5%, respectively), while China, Bangladesh, Türkiye, the Philippines, South Africa, and Brazil contributed one study each (4.8%,

respectively) (Figure 2). This distribution describes the geographical coverage of the selected literature rather than the relative prevalence or severity of contamination across countries. The studies addressed different regional priorities, with United States studies predominantly investigating microbial water quality predictive monitoring and beach-management conditions, while studies from Asia and Africa provided evidence on plastic debris, potentially toxic elements, hydrocarbons, and other chemical pollutants. Classified by contaminant type, microplastics and other plastic debris were reported in six studies (28.6%), followed by microbial and faecal contamination in nine studies (42.9%), potentially toxic elements in two studies (9.5%), consumer-related chemicals, pesticides and, hydrocarbons all had one study each (4.8%), and persistent organic pollutants in one study (4.8%). These categories are non-exclusive because [18] investigated both phthalates and polychlorinated biphenyls (PCBs), resulting in 22 category assignments across the 21 included studies. The percentages therefore represent the proportion of included studies reporting each contaminant category and should not be interpreted as mutually exclusive contributions to the evidence base (Table 1).

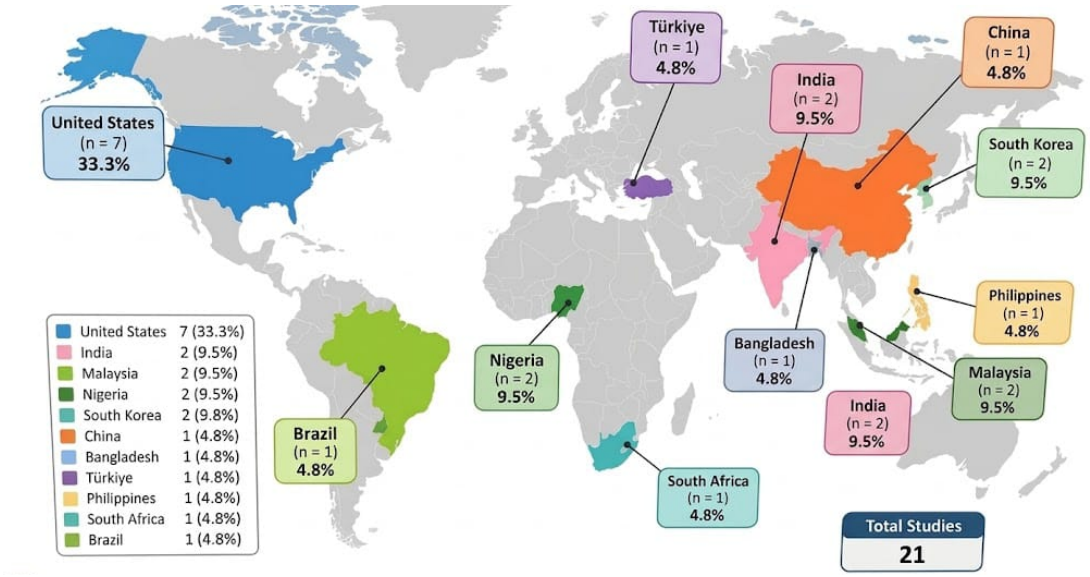


Figure 2. Geographical distribution of the 21 included primary studies. The figure describes the evidence base, not the prevalence of contamination by country.

Table 1. Categorisation of the 21 studies according to Contaminant types.

Contaminant Category	Studies Identified	Number of Studies	Percentage of 21
Microplastics and other plastic debris	[4,9,27–30]	6	28.6%
Microbial and faecal contamination	[14,20,21,31–36]	9	42.9%
Pesticides	[6]	1	4.8%
Potentially toxic elements (PTEs)	[15,16]	2	9.5%
Hydrocarbons	[17]	1	4.8%
Persistent organic pollutants (POPs)	* [18]—PCBs	1	4.8%
Consumer-related chemicals	* [18]—phthalates; [19]—personal-care chemicals	2 *	4.8%
Total	21 unique studies	22	100.0%

N/B: * [18] is repeated twice because of the contamination category, bringing the paper count to 22 instead of 21. Percentage is based on 21 unique studies.

3.2. Quantitative Distribution of Microplastic and Plastic Contamination

Across aquatic and sediment matrices, studies reported substantial quantitative variation in microplastic abundance. In beach and coastal environments, [9] recovered microplastics across all evaluated Haichow Bay beaches at a mean abundance of 106.50 ± 34.41 items/kg, with fibers and fragments comprising over 90% of particles smaller than 1 mm. Similarly, Nalwade et al. [29] recorded macro- and mesoplastic debris densities on Indian recreational beaches reaching 0.173 ± 0.10 items/m^2 at Bhatye Beach and 0.166 ± 0.19 items/m^2 at Aare-Ware Beach. Seasonal variations were also documented, with Nalwade et al. [29] observing a near-doubling of macroplastic accumulation during the Southwest Monsoon. Escañan et al. [30] reported higher wet-season microplastic abundance along Sarangani Bay urban beaches (0.047 particles/g) than during the dry season (0.015 particles/g) representing a 213% increase.

In enclosed and inland water bodies, Islam et al. [27] detected microplastics in all 30 water and 30 sediment samples from Nikli Lake. The reported mean concentrations were 98.167 ± 12.849 items/m^3 in water and 109.667 ± 10.892 items/kg dry weight in sediment. Polypropylene and polyethylene were the dominant polymers accounting for 53% and 43% respectively. In Lake Hazar, Varol et al. [28] confirmed microplastics in all sampled surface-water and sediment samples, with surface-water concentrations ranging 74 to 1091 items/m^3 and sediment concentrations from 88 to 213 items/kg wet weight. Shoreline water concentrations were significantly higher than those recorded at limnetic sites. The sediment values from Nikli Lake and Lake Hazar are retained in their original reporting forms because dry-weight and wet-weight measurements are not directly comparable. Similarly, water concentrations and sediment concentrations are presented separately because their units represent different environmental matrices (Figure 3).

Temporal variation was also evident in recreational river environments. Chandrakanthan et al. [4] reported Salt River surface-water microplastic concentrations increasing from 27,798 MPs/m^3 at 08:00 to 222,391 MPs/m3 at 16:00, representing approximately an eight-fold difference between the reported early-morning and peak-activity measurements. The reported observations indicate substantial temporal variation during recreational use; however, the complete sampling sequence, rather than only two selected time points, should be represented when reproducing the temporal pattern in Figure 4. In swimming-pool environments, microplastics have also been reported, with the relevant evidence including [4] and Moraczewska-Majkut et al. [37] (Figure 4).

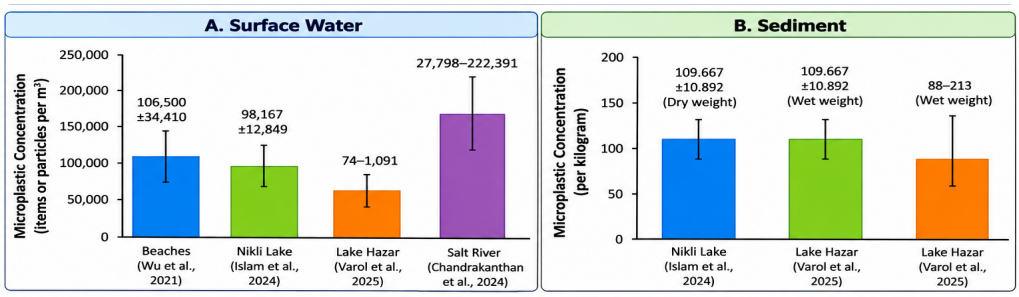


Figure 3. Microplastics concentrations in recreational environments: (**A**) Surface Water [4,9,27,28] and (**B**) Sediment [27,28]. Note: Water concentrations are assessed as items or particles per cubic metre, while sediment concentrations are expressed per kilogram. Sediments reported on wet-weight bases are identified separately and are treated as directly comparable.

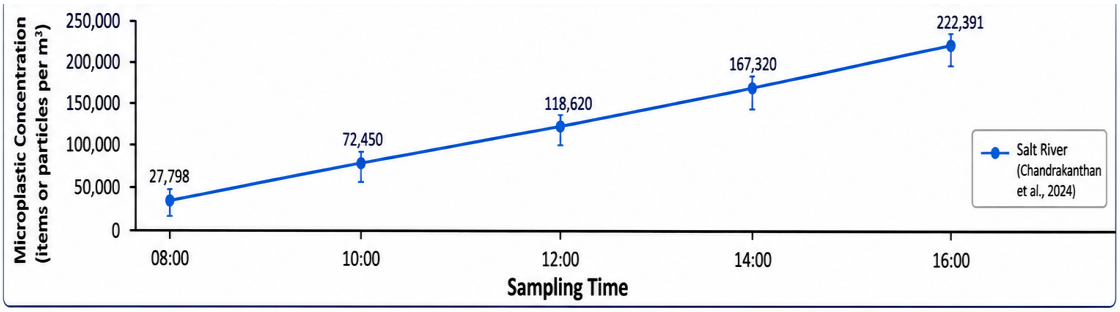


Figure 4. Temporal Variations in Microplastic Concentration in Salt River Surface Water by Chandrakanthan et al. [4].

3.3. Biological Occurrence and Chemical Contamination

Beyond abiotic environmental matrices, the reviewed studies documented microplastics and chemical pollutants in biological samples and across multiple environmental compartments (Table 2). Varol et al. [28] recovered microplastics from the gastrointestinal tracts of 28 out of 80 sampled fish in Lake Hazar. This represents a detection occurrence of 35% among the examined fish. Chemical monitoring identified diverse inorganic and organic pollutants across recreational environments. Ediagbonya et al. [17] quantified total petroleum hydrocarbons (TPH) at Araromi Beach, recording 16.95 mg/L in water, 4.22 mg/kg in sediment, and 2.02 mg/kg in fish tissue. In coastal ecosystems, [18] investigated six phthalate esters and 23 polychlorinated biphenyls (PCBs) in Lagos coastal waters and sediments. Santos et al. [19] identified targeted personal-care chemical compounds above limits of quantification in recreational waters.

Regarding agricultural runoff, [6] assessed 12 pesticides across three recreational lake watersheds and identified urban-runoff systems as major contributors. Imidacloprid concentrations exceeded acute and chronic invertebrate ecotoxicity thresholds during 11% and 61% of sampling periods, respectively. Studies of potentially toxic elements also reported measurable concentrations in recreational waters. Nayan et al. [15] assessed seven metals across 22 stations in Taiping Lake Gardens and reported lead concentrations exceeding the comparison standards used in that study, alongside iron concentrations reaching 1.218 mg/L. Because the specific guideline and threshold applied to the reported lead exceedance are not identified in the extracted evidence, the finding should not be presented as a general breach of recreational-water safety standards. Sulaiman et al. [16] reported mean concentrations of Fe (1.71 mg/L), Mn (0.69 mg/L), Zn (0.08 mg/L), Cu (0.019 mg/L) and Pb (0.013 mg/L) in a tropical recreational lake.

Table 2. Study-by-study evidence extraction and principal planning relevance.

Study	Country/Setting	Recreational Environment	Contaminant	Key Empirical Finding	Planning Relevance
[9]	China	Haichow Bay beaches	Microplastics	106.50 ± 34.41 items/kg; >90% <1 mm; resort beaches highest	Tourism intensity and land-based plastic inputs require integrated beach management
[27]	Bangladesh	Nikli Lake	Microplastics	30 water + 30 sediment samples; PP 53%, PE 43%	Sewage, fishing waste and agricultural runoff require catchment planning
[28]	Türkiye	Lake Hazar	Microplastics	Water 74–1091 items/m^3; sediment 88–213 items/kg; 28/80 fish positive	Shoreline and fishing/recreation zones require spatial source control
[4]	USA	Salt River and pools	Microplastics	Salt River 27,798–222,391 MPs/m^3; pools 59,160–254,574 MPs/m^3	Monitoring should reflect recreational intensity and facility use
[29]	India	Bhatye and Aare-Ware beaches	Macro/mesoplastics	0.173 ± 0.10 and 0.166 ± 0.19 items/m^2	Seasonal and monsoon-sensitive waste planning
[30]	Philippines	Sarangani Bay beaches	Microplastics	Urban wet-season concentration 0.047 particles/g; dry season 0.015	Seasonal runoff and urban pressure require targeted management
[14]	India	Five Chennai beaches	Faecal contamination	Up to 4.2 × 10^5 CFU/mL	Sewage and drainage control should precede repeated beach advisories
[31]	South Africa	Kidd's Beach	Microbial contamination	Enterococcus 64–168 CFU/100 mL	Continuous spatial monitoring and pollution-source control
[32]	USA	Marine recreational beach	Pathogens	Pathogen occurrence and concentration associated with bather density	High-use periods should inform microbial monitoring
[33]	USA	Nine Chicago beaches	Fecal contamination	Automated continuous monitoring system developed	Real-time monitoring can shorten decision delays
[34]	USA	Four Lake Michigan beaches	E. coli	Real-time nowcasting models evaluated	Forecasting can support timely advisories
[21]	South Korea	Haeundae and Gwangalli beaches	Fecal contamination	ANN/SVR nowcasting using environmental variables	Machine learning can support activity-sensitive management
[35]	USA	316 Florida beaches	Fecal indicators	>150,000 measurements per FIB; management conditions associated with exceedances	Beach morphology and management should be treated as water-quality variables
[36]	USA	Calumet Beach	E. coli	146-m barrier altered nearshore E. coli/turbidity patterns	Infrastructure must be designed around local hydrodynamics
[20]	South Korea	Gwangalli Beach	E. coli and ARGs	Outfall scenarios predicted 46–99% reductions	Wastewater-outfall location and depth are planning variables
[6]	USA	Three recreational lakes	Pesticides	Urban-runoff lake had highest loading; imidacloprid exceeded acute/chronic levels 11%/61%	Catchment land use and stormwater controls are essential
[15]	Malaysia	Taiping Lake Gardens	Heavy metals	22 stations; seven metals; lead exceeded standards at observation	Spatial metal surveillance should inform recreational use
[16]	Malaysia	Jengka recreational lake	Heavy metals	Fe 1.71, Mn 0.69, Zn 0.08, Cu 0.019, Pb 0.013 mg/L	Monitoring and health-risk assessment should accompany use
[17]	Nigeria	Araromi Beach	TPH	16.95 mg/L water; 4.22 mg/kg sediment; 2.02 mg/kg fish	Hydrocarbon source control and food-chain surveillance
[18]	Nigeria	Lagos coastal waters/sediments	Phthalates and PCBs	Six phthalates and 23 PCBs assessed; several exceeded study comparison limits	Plastic-associated chemicals require integrated monitoring
[19]	Brazil	Recreational waters/pools	Personal-care chemicals	Three of six samples contained target analytes above LOQ	Emerging-contaminant surveillance should complement routine monitoring

3.4. Microbial Contamination and Infrastructure Performance

Microbial assessments presented in Table 3 demonstrated faecal indicator contamination associated with wastewater inputs and bather density. Begum et al. [14] recorded faecal coliform concentrations across five major Chennai recreational beaches reaching up to 4.2×10^5 CFU/mL, with spatial variability associated with river mouths and untreated domestic discharges. At Kidd's Beach, presumptive Enterococcus counts ranged from 64 to 168 CFU/100 mL, while PCR analysis confirmed the presence of pathogenic species [31]. In marine recreational environments, [32] identified human waterborne pathogens, including *Cryptosporidium parvum*, *Giardia duodenalis* and *Enterocytozoon bieneusi*, with reported occurrence and concentrations significantly associated with bather density.

Evaluations of management policies and structural interventions revealed varied environmental responses. Analysing more than 150,000 measurements across 316 Florida beaches, [35] found that lower enterococci exceedance rates were associated with open-coast morphology, lower human and animal densities, bird-management policies, beach renourishment, lifeguard employment, the absence of nearby marinas and active stormwater management. Physical engineering interventions, however, did not produce uniformly favourable outcomes. At Calumet Beach, [36] found that mean *E. coli* concentrations and turbidity were higher inside a 146-m filtering barrier than at the southern control transect, a pattern attributed to local hydrodynamics and sediment resuspension. In another intervention study, [20] combined field monitoring and hydrodynamic modelling at Gwangalli Beach and reported that alternative offshore outfall configurations achieved predicted reductions of 46–99% in *E. coli* and antibiotic-resistance genes.

Table 3. Contamination pathways, empirical evidence and planning responses.

Contamination Pathway	Empirical Evidence	Planning Response	Authors
Tourism and visitor pressure	Higher microplastics at resort beaches; tourism and public littering linked to beach debris	Visitor-capacity management, waste infrastructure and behaviour interventions	[9,30]
Recreational activity	Salt River peak concentrations; bather density associated with pathogens	Activity-sensitive monitoring and temporal management	[4,38]
Agricultural and urban runoff	Pesticides entering recreational lakes; urban watershed highest loading	Catchment zoning, stormwater interception and riparian buffers	[6]
Sewage and wastewater	High faecal contamination at Chennai beaches; outfall effects at Gwangalli	Sanitation, wastewater treatment and evidence-based outfall design	[6]
Fishing activity	Fishing waste identified as a Nikli Lake source; fishing/recreation identified as Lake Hazar source	Fishing-zone management and retrieval/waste programmes	[14,20]
Beach litter	Plastic debris dominates multiple beach studies	Waste collection, source reduction and polluter-pays mechanisms	[4,27]
Hydrocarbons	High TPH in Araromi water, sediment and fish	Hydrocarbon source control, zoning and food-chain surveillance	[9,29,30]
Plastic-associated chemicals	Phthalates and PCBs detected in Lagos coastal samples	Chemical monitoring linked to plastic-waste management	[17]
Personal-care chemicals	Target compounds detected in recreational waters	Emerging-contaminant surveillance and source reduction	[18]
Facility- generated contamination	Microplastics detected in swimming pools; equipment and swimwear implicated	Material selection, filtration, maintenance and user-management controls	[19]

4. Discussion

4.1. Recreational Activity, Contaminant Mobilisation and Spatial Variation

The reviewed evidence identifies microbial contamination and microplastics as the most frequently reported contaminant groups, occurring in nine and six studies, respectively. The occurrence of plastics across recreational environments, including coastal beaches, inland lakes, rivers, swimming pools and water parks, reflects their persistence and extensive environmental distribution. Fragmentation of larger debris through weathering, abrasion and other environmental processes provides an important pathway for the generation of secondary microplastics [12]. Global plastic waste generation and mismanagement further increase the potential for plastics to enter aquatic environments through land-based pathways, particularly where waste management systems are inadequate [7]. However, the substantial variation in reported concentrations demonstrates that contamination is not uniformly distributed within or between recreational systems.

In Nikli Lake, for example, microplastics were detected in all sampled water and sediment samples, with polypropylene and polyethylene accounting for 53% and 43% of the identified polymers, respectively [27]. A similarly widespread occurrence was reported in Lake Hazar, where microplastics were detected across all sampled surface-water and sediment sites, although concentrations differed considerably between shoreline and limnetic locations [28]. Such differences are consistent with the understanding that microplastic transport and accumulation

are strongly influenced by particle characteristics, hydrodynamic conditions and environmental compartment. Particle density, shape and biological fouling can alter the position of plastics within the water column and influence whether particles remain suspended, are transported laterally or become deposited in sediments [39]. Consequently, the distribution observed at a recreational site may reflect both local inputs and redistribution processes operating beyond the immediate area of human use. This distinction is particularly important because recreational activities are generally concentrated along accessible shorelines. Measurements obtained from offshore or lake-wide sampling may therefore fail to represent contamination conditions within areas of direct human contact. The spatial heterogeneity of microplastics has also been demonstrated across coastal and riverine environments, where transport pathways and local accumulation processes can produce substantial differences over relatively short distances [40]. Microplastics may be transported by currents and subsequently deposited or remobilised according to local hydrodynamic conditions, making contamination patterns dynamic rather than fixed. This provides a stronger basis for interpreting differences between shoreline and limnetic locations as part of a transport process rather than simply as differences in the amount of plastic entering each site.

Spatial variation is also not restricted to inland waters. Differences in microplastic abundance have also been reported among beaches within the same coastal systems, indicating that contaminant accumulation may be shaped by local shoreline characteristics, hydrodynamic conditions and proximity to contamination sources [9]. The spatially uneven distribution of microplastics therefore provides a basis for considering how contaminants are redistributed after entering recreational environments. This becomes particularly evident when the evidence is examined across time. At the Salt River, microplastic concentrations increased from 27,798 MPs/m^3 at 08:00 to 222,391 MPs/m^3 at 16:00, coinciding with periods of greater recreational activity [4]. Although this temporal association suggests a possible relationship between recreational activity and particle abundance, it does not independently establish causation. Direct inputs from recreational users, sediment disturbance and mobilisation of previously deposited particles are plausible explanations, although their relative contributions cannot be determined from concentration data alone.

The importance of temporal variation is reinforced by the seasonal patterns observed in coastal environments. Nalwade et al. [29] recorded substantially greater macroplastic accumulation during the Southwest Monsoon, while [30] reported microplastic concentrations of 0.047 particles/g during the wet season compared with 0.015 particles/g during the dry season. These findings extend the interpretation of contamination beyond recreational activity alone by showing that hydrological conditions can also alter the distribution and accumulation of pollutants. Rainfall, surface runoff, changes in river discharge and shoreline transport can modify the movement and deposition of plastic materials, particularly where recreational waters are connected to larger catchments [7,40]. Recreational contamination therefore appears to vary through the combined influence of site characteristics, hydrological conditions and patterns of human use rather than remaining constant across space or time.

This interaction is also relevant in enclosed recreational facilities. The high microplastic concentrations reported in community swimming pools and water parks demonstrate that substantial particle loads can occur even where contamination is not directly influenced by catchment runoff or coastal processes [4,37]. In these settings, limited water exchange, repeated human contact and differences in filtration and maintenance may influence particle persistence. The WHO framework for recreational water quality similarly emphasises that water quality management must be adapted to the characteristics and risks of individual recreational settings rather than relying on a single generic approach [8]. Although the available evidence does not permit attribution to a single process, the findings show that recreational activity can occur within environmental systems where contaminant inputs and removal processes operate differently from those of open coastal and inland waters. This distinction is important because the occurrence of microplastics in recreational environments cannot be explained through one common transport mechanism..

4.2. Biological Exposure and Chemical Contamination

The spatial and temporal occurrence of contaminants in water and sediment also has implications for biological exposure. Microplastics were detected in the gastrointestinal tracts of 28 out of 80 fish sampled from Lake Hazar (35.0%; [28]). This indicates that aquatic organisms encounter particles in recreational lake systems, but does not demonstrate tissue accumulation, physiological effects or human exposure through fish consumption. Ingestion represents one potential pathway of contamination into aquatic organisms, with its significance depending on particle characteristics, feeding behaviour, retention time and species. Microplastics may also interact with other aquatic contaminants. Although they can concentrate persistent organic pollutants [12], their transfer and biological effects depend on environmental conditions. Hydrophobic organic contaminants have also

been associated with polymer-specific microplastics in urban rivers and estuaries [41]. However, such associations do not necessarily establish enhanced biological uptake or toxicity.

Chemical contamination across environmental matrices further illustrates the complexity of biological exposure. At Araromi Beach, [17] detected total petroleum hydrocarbons in water, sediment and fish tissue. However, these findings do not establish the direction of transfer because fish may be exposed through water, sediment, diet or combined pathways. Similarly, [18] identified six phthalate esters and 23 PCB congeners in Lagos coastal waters and sediments, while [19] reported personal-care chemicals above limits of quantification in recreational waters. These findings indicate that recreational environments may contain contaminants beyond visible litter and microbial indicators. Contamination may also originate beyond recreational sites through surrounding watershed processes. Satiroff et al. [6] found that imidacloprid exceeded acute and chronic invertebrate ecotoxicity thresholds during 11% and 61% of sampling periods, respectively. This suggests that recurring urban and catchment runoff may create ecological concerns through repeated chemical inputs, even when acute thresholds are not consistently exceeded.

Similar concerns arise from potentially toxic elements. Nayan et al. [15] reported lead concentrations exceeding the standards applied in their study, alongside iron concentrations reaching 1.218 mg/L in Taiping Lake Gardens. Sulaiman et al. [16] also documented Fe, Mn, Zn, Cu and Pb in a tropical recreational lake. The ecological significance of these elements depends on their concentrations, chemical forms, persistence, exposure duration and relevant environmental thresholds. Their co-occurrence should not automatically be interpreted as evidence of synergistic toxicity. Although microplastics may interact with organic contaminants and metals, the implications for biological exposure depend on the properties of the particles and associated contaminants [12,42,43].

Plastic degradation and chemical contamination also require careful distinction. Environmental weathering causes surface deterioration, oxidation and fragmentation but does not necessarily result in complete depolymerisation into constituent monomers. PET hydrolysis involves cleavage of ester bonds and may ultimately release ethylene glycol and terephthalic acid. However, this process is considerably slower under ordinary near-neutral aquatic conditions than under the elevated temperatures and controlled chemical conditions used in industrial recycling. Thus, exposure to approximately 30 °C alone does not demonstrate rapid PET decomposition or complete monomer release. Phthalate esters are not PET degradation products; they are separate additives used in certain plastic formulations. Their detection may reflect migration, leaching, waste inputs or other sources. Accordingly, microplastic particles, monomers and additives represent distinct forms of environmental evidence and should not independently be taken as proof of biological exposure or toxicological effects [12,13].

4.3. Microbial Contamination, Spatial Characteristics and Infrastructure Performance

The diversity of chemical contaminants identified across the reviewed environments is mirrored by the microbial evidence, which similarly demonstrates that contamination conditions are shaped by both external inputs and processes occurring within recreational spaces. At Chennai beaches, faecal coliform concentrations reached 4.2×10^5 CFU/mL and were spatially associated with river mouths and untreated domestic discharges [14]. This pattern demonstrates that contamination measured at the recreational interface may originate from processes operating upstream or outside the immediate recreational area. The location of river outlets and wastewater inputs can therefore influence microbial conditions at beaches independently of the activities occurring directly on the shoreline. This catchment influence is important because recreational exposure does not necessarily correspond closely with a single measured indicator of water quality. Fewtrell and Kay [3] in their review of epidemiological and quantitative microbial risk assessment evidence, reported that bathers generally experience an elevated risk of gastrointestinal illness but that the relationship between illness and conventional faecal indicator measurements is not always consistent, particularly at sites affected by non-point-source pollution. Their findings reinforce the importance of identifying contamination sources and transport pathways rather than interpreting indicator concentrations in isolation. At the same time, the relationship between recreational activity and microbial contamination is demonstrated by the significant association between bather density and the occurrence of *Cryptosporidium parvum*, *Giardia duodenalis* and *Enterocytozoon bieneusi* reported by [32]. Recreational exposure therefore represents both an outcome of contamination and a factor that can influence short-term contamination conditions. Korajkic et al. [38] similarly emphasised the importance of understanding relationships between faecal indicators and pathogens in recreational water settings, while noting that indicator organisms do not necessarily provide a direct measure of every pathogen of public health concern. When considered alongside the wastewater-related contamination observed at Chennai beaches, these findings suggest that microbial conditions may result from the interaction between persistent background pollution and shorter-term changes associated with human use.

The importance of site characteristics in mediating these contamination patterns is further demonstrated by the analysis of 316 Florida beaches. Kelly et al. [35] found that lower enterococci exceedance rates were associated with open-coast morphology, lower human and animal densities, bird management, beach renourishment, lifeguard employment, the absence of nearby marinas and active stormwater management. These associations indicate that microbial water quality reflects the combined influence of physical setting, surrounding sources and management conditions. However, because several of these variables operate simultaneously, individual associations should not be interpreted as direct evidence of causation. Rather, the findings show that recreational water quality is influenced by a combination of environmental and human factors that may vary substantially between sites.

The importance of continuous observation is also illustrated by [33], who demonstrated the feasibility of automated continuous recreational water quality monitoring across nine Chicago beaches. Continuous monitoring is particularly relevant where microbial concentrations can change rapidly in response to rainfall, runoff, bather activity and other short-term processes. It also supports the broader principle that recreational water management should be based on timely assessment of changing conditions rather than on isolated measurements alone. This relationship between physical conditions and contamination becomes particularly apparent when management interventions alter local environmental processes. At Calumet Beach, the installation of a 146-m filtering barrier did not consistently produce the intended improvement in water quality. Mean *E. coli* concentrations and turbidity were higher inside the barrier than at the southern control transect, with sediment resuspension, accumulated algae, shallowing and local hydrodynamic conditions identified as possible contributing factors [36]. The outcome demonstrates that interventions designed to control contamination can also modify the conditions governing contaminant distribution, particularly where water circulation and sediment processes are altered.

The importance of spatial configuration is further demonstrated by the modelling study at Gwangalli Beach. [20] showed that alternative offshore outfall configurations were predicted to reduce *E. coli* and antibiotic-resistance gene concentrations by between 46% and 99%. Although these results cannot be directly compared with the Calumet Beach barrier because the studies addressed different environmental systems and intervention strategies, they show that the position of contamination sources relative to local water movement can substantially influence water quality conditions. The predicted reductions should not, however, be interpreted as measured post-intervention improvements. The contrasting findings therefore draw attention to the importance of understanding site-specific transport processes before implementing structural or engineering interventions. This is consistent with the preventive, site-specific risk-management approach advocated by [8], which places assessment, surveillance and control of hazards at the centre of recreational water management.

4.4. Methodological Constraints and Comparability of the Evidence

The marked differences in contaminant concentrations observed across the reviewed studies must also be interpreted in relation to methodological variation. Microplastic abundance was reported using different matrices, particle-size thresholds, extraction procedures, analytical techniques and measurement units, including items per cubic metre, particles per litre, particles per gram and items per kilogram expressed on either a dry- or wet-weight basis [27,28,30]. These differences are not merely technical details. Cowger et al. [25] identified substantial problems with reproducibility and comparability in microplastic research arising from inconsistent reporting of sampling, preparation, identification, categorisation and quantification procedures. As a result, large differences in reported concentrations cannot be interpreted solely as evidence of differences in environmental contamination.

Particle size provides a particularly important example. Microplastic transport and environmental retention can vary with particle size, shape and density, while small particles may behave differently from larger fragments during transport and deposition [39]. Differences in particle-size thresholds and analytical procedures can therefore influence reported abundance and apparent spatial patterns. Consequently, a study that detects a greater proportion of smaller particles may report substantially different concentrations from another study using a larger minimum detection threshold even when the underlying environmental contamination is comparable.

Temporal variation introduces an additional layer of complexity. The wet-season increase reported by [30], the monsoon-related accumulation observed by [29] and the within-day increase reported by [4] demonstrate that contamination can vary across seasonal and short-term temporal scales. Hydrodynamic transport can further redistribute floating debris over time, meaning that the location at which contamination is measured may represent a temporary accumulation state rather than a permanent source area [40]. These findings make comparisons between studies particularly difficult where sampling was conducted at different times of the year or over different monitoring durations. A single sampling campaign may therefore capture only one stage within a broader cycle of contaminant mobilisation, transport and deposition.

Spatial differences create a similar challenge. The higher concentrations observed in shoreline areas of Lake Hazar compared with limnetic locations demonstrate that the selection of sampling points can influence the apparent magnitude of contamination [28]. This is particularly relevant to recreational environments because areas of highest contaminant concentration may not correspond with areas selected for routine environmental monitoring. Where sampling is restricted to a small number of points, local accumulation zones or areas of intensive recreational exposure may remain underrepresented. The transport literature further indicates that plastics can be redistributed by currents and subsequently concentrated in particular locations, reinforcing the need to consider site-specific measurements [40].

These methodological differences also affect the detection of smaller particles. Variation in analytical detection limits and particle-size thresholds can lead to different estimates of microplastic abundance even where environmental conditions are broadly similar. Smaller microplastic fractions and nanoplastics remain particularly difficult to identify and quantify consistently. Cowger et al. [25] therefore emphasised harmonised reporting and quality assurance as prerequisites for improving the comparability and reproducibility of microplastic studies. The methodological heterogeneity across the evidence base consequently requires quantitative differences between recreational environments to be interpreted as context-dependent observations rather than as directly comparable measures of relative contamination severity. A further limitation is that most included studies focused on contaminant monitoring and occurrence rather than direct evaluations of recreational planning interventions. The central issue is not simply whether one site contains more contaminants than another, but whether the studies have measured comparable environmental compartments using sufficiently similar sampling and analytical approaches. This distinction is particularly important for planning and public health decision-making because [8] recommends risk-management approaches that integrate site characteristics, surveillance, exposure pathways and appropriate monitoring rather than relying on a single contaminant concentration as a universal indicator of recreational water safety.

5. Implications for Recreational Planning and Environmental Management

For recreational planning practice, the evidence supports a transition from site-centred design to systems-based environmental planning. New facilities should be evaluated within their catchment context, with source inventories completed before capacity is expanded. Existing beaches and lakes should prioritise stormwater and wastewater pathways, waste infrastructure and high-use zones where contamination is likely to accumulate. Where recreational intensity changes sharply over time, monitoring and management should be timed to periods of greatest environmental and user pressure. Site-specific assessments should also distinguish between contaminant occurrence and demonstrated exposure risks when informing recreational-use decisions.

For policy and investment, contamination prevention can protect both environmental quality and the recreational function of beaches, lakes and waterways. Investments in sanitation, drainage, waste collection, catchment protection and predictive monitoring can reduce the likelihood of closures, reputational damage, ecological degradation and repeated remediation. Planning decisions should consequently consider environmental quality as part of the long-term economic and social value of recreational assets rather than treating contamination control as a separate regulatory cost. However, the effectiveness of these proposed planning responses requires further empirical evaluation.

6. Limitations

An important methodological limitation concerns the availability of historical search and screening documentation. Although the literature searches were conducted across four scientific databases, the original database exports, complete search histories, deduplication records and stage-by-stage screening logs were unavailable for independent audit. Consequently, database-specific retrieval totals and numerical screening exclusions could not be verified retrospectively. To avoid introducing unsupported information, reconstructed PRISMA counts and undocumented search strings have not been presented. The review therefore adopts a PRISMA 2020-informed critical evidence synthesis approach rather than presenting itself as a fully reproducible systematic review. Nevertheless, the 21 primary empirical studies retained for the analysis provide the evidence base for the thematic assessment of contamination sources, exposure pathways and recreational planning implications. The absence of the original search records limits independent replication of the literature identification and selection process and should be considered when interpreting the scope of the evidence synthesis.

A further limitation is the methodological heterogeneity of the included studies. Differences in environmental matrices, sampling frequencies, particle-size thresholds, analytical methods, contaminant definitions and reporting units prevented formal quantitative pooling through meta-analysis. Accordingly, the review employed structured narrative synthesis supported by study-level quantitative reporting. Furthermore, the predominantly observational

nature of the included empirical studies limits the extent to which causal relationships can be established, particularly regarding the long-term effectiveness of specific environmental management and recreational planning interventions. Geographical representation was also uneven, while some contaminant categories were supported by only one or two studies. Additionally, most included studies focused on contaminant occurrence and environmental monitoring rather than directly evaluating the effectiveness of recreational planning interventions. Reliance on published literature may also have introduced publication bias, geographical representation bias and limitations associated with the coverage of the selected databases. These constraints limit the generalisability of the findings and highlight the need for larger, standardised, multi-season investigations that directly connect contamination measurements with recreational intensity, human and ecological exposure pathways, and the effectiveness of planning and management interventions.

7. Conclusions

Recreational environments should no longer be planned as spaces in which environmental contamination is considered only after recreational development has occurred. The evidence synthesised in this review demonstrates that contamination is spatially and temporally structured across beaches, lakes, rivers and swimming facilities and that recreational conditions interact with catchment-derived inputs, wastewater, runoff, fishing, tourism, textiles, equipment and waste management. Microplastics and microbial contamination were the most frequently represented contaminant groups among the 21 studies, while pesticides, potentially toxic elements, hydrocarbons, phthalates, PCBs and personal-care chemicals further demonstrate that recreational water quality is a multi-contaminant planning issue. The most defensible response is therefore a source-to-receptor approach that integrates catchment planning, zoning, sanitation, waste infrastructure, activity-sensitive monitoring, predictive tools and transparent risk management. Such integration can support a shift from reactive closure towards prevention while protecting both environmental quality and public access. Future research should strengthen standardised measurement and explicitly evaluate whether planning interventions reduce contaminant loads and potential exposure risks.

Author Contributions

D.E.J.: conceptualization, methodology, writing—original draft preparation; I.D.J.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

All the data used in the paper are publicly available in the various studies assessed and included in the study.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) and Grammarly as writing-assistance tools. ChatGPT was used to assist with language refinement, improving clarity and readability, and reorganising selected passages for coherence and consistency. Grammarly was used for grammar, spelling, punctuation and language correction. Neither tool was used to generate primary research data, conduct environmental sampling, perform laboratory analyses, determine empirical findings or independently validate the scientific evidence. The authors critically reviewed and revised the AI-assisted outputs, verified the scientific content against the cited literature to the extent possible, and accept full responsibility for the accuracy, originality, integrity and final content of the manuscript.

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