



Systematic Review

Emerging Contaminants in Aquaculture Production: Environmental and Human Health Risks

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Abstract

The contamination of aquaculture products and effluents by Emerging Contaminants (ECs)—originating from both direct chemical applications and peripheral industrial activities—represents a critical global concern due to the environmental and public health risks associated with their persistence, bioaccumulation, and environmental dispersion. This systematic review aimed to synthesize the available scientific evidence on the occurrence, sources, environmental and human health impacts, and mitigation strategies of ECs in aquaculture production systems. A systematic literature search was conducted following the PRISMA 2020 guidelines across the Web of Science, Scopus, and Google Scholar databases. Studies were selected according to predefined eligibility criteria, resulting in a total of 137 studies included in this review. The findings indicate that these pollutants accumulate within the tissues of farmed organisms, posing direct ingestion risks to humans, while contaminated effluents facilitate the widespread degradation of receiving water bodies. Given their environmental persistence and ubiquitous distribution, there is an urgent need for advanced analytical methodologies, robust regulatory frameworks, and the implementation of sustainable treatment technologies—such as advanced oxidation processes and recirculating aquaculture systems—alongside strategies for reducing antibiotics and microplastics. These measures are essential to mitigate the prevalence of ECs and safeguard both ecosystem integrity and human health.

Keywords: disinfectants; microplastics; pharmaceuticals; pesticides



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1. Introduction

The aquaculture industry contributes significantly to global food security and socio-economic development through the intensive production of high-nutritional-value food [1–4]. Indeed, the sector's expansion is so accelerated that global aquaculture and fisheries production has reached 223.2 million tonnes [5]. Nevertheless, this demographic and industrial increase drives the excessive application of various pharmaceuticals, water disinfectants, hormones, and antibiotics to optimise productivity and treat bacterial diseases [6–8]. As a direct consequence, these poor management practices facilitate the persistent accumulation of Emerging Contaminants (ECs) in both commercial products and surrounding effluents [6,9–12]. Although these toxic chemical compounds derive from internal farm management, they also enter through external anthropogenic sources

such as municipal discharges, agricultural run-off, and hospital waste [13–15]. When ECs are not adequately degraded, they persist in water or sediments, progressively bioaccumulating in the tissues of cultured organisms [11,16,17]. Subsequently, the uncontrolled discharge of these wastewaters into natural ecosystems triggers severe environmental degradation, which precipitates the proliferation of antimicrobial resistance and biological dysbiosis [6,11,18,19]. Currently, the primary challenge lies in the high complexity of origin sources and the extensive diversity of chemical compounds present simultaneously. Unfortunately, this scenario is exacerbated by the lack of systematic technical monitoring and the absence of efficient regulatory frameworks within production units.

Previous research has analysed the prevalence of specific pharmaceuticals and pesticides in water matrices in isolation, successfully delineating acute toxicity in aquatic species [13,20–22]. These bibliographical studies offer clear operational advantages by identifying individual incorporation pathways and environmental persistence mechanisms [6,7,23]. However, the currently available scientific literature is fragmented, revealing a critical knowledge gap regarding the collective impact of ECs on aquaculture systems [11,12]. Furthermore, preceding reviews fail to rigorously assess the risks of occupational exposure and chronic health damage sustained by personnel within aquaculture facilities.

This systematic review adopts an integrative approach to synthesise current scientific evidence regarding the sources, exposure pathways, and mechanisms of action of the most frequently reported emerging contaminants. The aim was to provide a conceptual framework that directly links the origins of aquaculture pollution with their respective ecotoxicological and sanitary risks. In this context, the specific effects of disinfectants, anaesthetics, antibiotics, hormones, pesticides, and microplastics on the environment, organisms, and humans are reviewed and detailed. The chronic presence of emerging contaminants can impair the health of aquatic organisms, alter ecosystem balance, generate occupational risks for workers, and result in residues in products destined for human consumption. Consequently, this evidence underscores the urgent need to transition towards sustainable technologies, such as Recirculating Aquaculture Systems (RAS) and Advanced Oxidation Processes (AOPs). The evidence compiled herein serves as a robust scientific foundation to guide the design of future experimental research in complex environmental matrices. Finally, these practical applications facilitate the development of public regulatory policies and optimise sanitary management strategies within the aquaculture sector.

2. Materials and Methods

A systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The PRISMA 2020 checklist was completed and is provided as Supplementary Materials (<https://www.mdpi.com/article/doi/s1>). The review protocol was retrospectively registered on the Open Science Framework (OSF) (<https://doi.org/10.17605/OSF.IO/6GNCM>). The review aimed to systematically identify, evaluate, and synthesize the available scientific evidence on the occurrence, sources, exposure pathways, environmental persistence, ecological impacts, human health risks, and mitigation strategies associated with emerging contaminants in aquaculture production systems.

2.1. Data Collection and Extraction

A systematic literature search was performed covering the period from 1982 to 2026 using three international scientific databases: Web of Science (Core Collection), Scopus, and Google Scholar, selected because of their broad coverage of environmental sciences, aquaculture, toxicology, and public health research. The review aimed to identify scientific evidence regarding the occurrence, sources, exposure pathways, environmental fate, eco-

logical effects, and human health implications of emerging contaminants associated with aquaculture production systems. The search strategy combined controlled vocabulary and free-text terms using Boolean operators (AND/OR). Search strings were adapted to the syntax requirements of each database. The following search strategy was applied in Google Scholar, Web of Science, and Scopus: (“emerging contaminants” OR “disinfectants” OR “pharmaceuticals” OR “hormones” OR “antibiotics” OR “anesthetics” OR “pesticides” OR “microplastics”) AND (“aquaculture” OR “intensive aquaculture” OR “aquaculture effluents” OR “recirculating aquaculture systems”) AND (“environmental risk” OR “human health risk”) AND (“occupational risks” OR “antibiotic resistance genes” OR “food safety”) AND (“advanced oxidation processes” OR “membrane filtration” OR “effluents”).

Following the initial search, 3490 records were identified (Google Scholar = 1612; Scopus = 1092; Web of Science = 786). After removing 1180 duplicate records, 2310 studies remained for title and abstract screening. During this stage, 1910 studies were excluded because they did not meet the predefined eligibility criteria, including studies unrelated to emerging contaminants, aquaculture production systems, antibiotic resistance genes, or environmental and human health risks. Subsequently, 410 articles underwent full-text assessment for eligibility. Of these, 273 studies were excluded because they lacked empirical evidence, did not satisfy the methodological inclusion criteria, or full-text access was unavailable. Finally, 137 studies fulfilled all eligibility criteria and were included in the qualitative synthesis. The complete study selection process is presented in the PRISMA flow diagram (Figure 1).

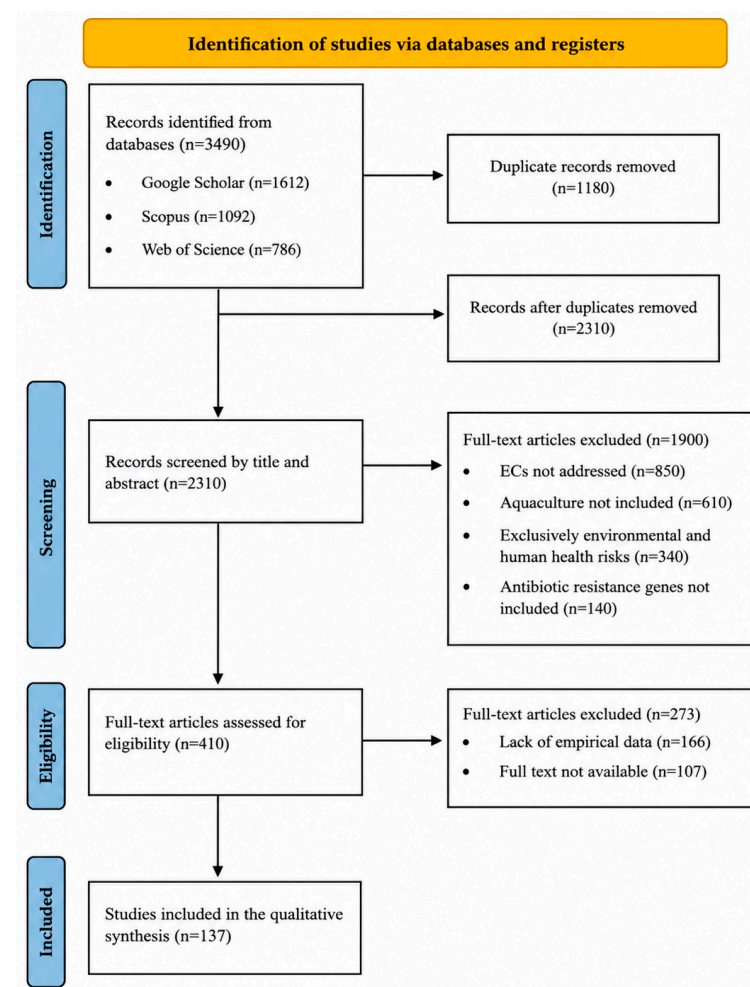


Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility, and inclusion process for the systematic review.

2.2. Inclusion and Exclusion Criteria

Studies were included in this review if they were peer-reviewed empirical investigations assessing the occurrence, sources, exposure pathways or impacts of emerging contaminants in aquaculture production systems. Eligible studies were required to evaluate disinfectants, pharmaceuticals, hormones, antibiotics, anesthetics, pesticides, microplastics, or antibiotic resistance genes in aquaculture environments, farmed organisms, occupational exposure, or food safety. Only articles with sufficient methodological detail were considered. Studies were excluded if they lacked empirical data, had insufficient methodological rigor, or were non-original research such as commentaries, editorials, conference abstracts, reviews, meta-analyses, or other non-peer-reviewed gray literature.

3. Emerging Contaminants

Emerging Contaminants (ECs), also known as contaminants of emerging concern, are a diverse group of chemicals of anthropogenic or natural origin. Many emerging contaminants are toxic, persistent and non-biodegradable, and are not regulated by most environmental regulations; however, they have been recently detected in environmental matrices due to their potential adverse effects on the environment and may influence ecology and public health [21,24–27].

These contaminants include a variety of substances such as pharmaceuticals, hormones, personal care products, pesticides, perfluorinated compounds, and microplastics, whose presence in aquatic systems is considered a risk [13,20–22]. The classification of emerging contaminants (ECs) is broad, also including antibiotics, industrial chemicals, and biological contaminants such as bacteria and viruses [28]. ECs include components of medicines, foods, disinfectants, personal care products and agrochemicals. ECs concentrate in some environments such as in wastewater, where the pollutants and pathogenic microorganisms mix [29].

Sources and Pathways of Entry into Aquaculture Systems

The sources and entry pathways of ECs into aquaculture systems are diverse and complex. One of the main pathways is the direct application of chemicals in aquaculture farms, such as antibiotics, antiparasitics, hormones, and disinfectants used to treat diseases and improve productivity [6,7]. The use of plastic materials in aquaculture infrastructure, such as nets, mesh, containers, and flotation systems, may contribute to the release of microplastics through physical or photochemical degradation [30]. Contaminants can enter aquaculture systems indirectly through water supplies, which may be contaminated by agricultural runoff and domestic, hospital, and industrial discharges that transport residues of pharmaceuticals, fertilizers, pesticides, and microplastics [20,23].

Another point source of ECs in aquaculture systems is wastewater treatment plants, which release effluents containing pharmaceutical residues, personal care products, and other chemicals directly into water bodies, where they are not completely removed during conventional treatment [31,32]. Nonpoint sources, such as agricultural fields, contribute pesticides and fertilizers, which can leach into groundwater or be carried by surface runoff to rivers and lakes [33]. In order to understand the dynamics of these contaminants, the sources and entry pathways of emerging contaminants (ECs) into aquaculture systems are schematised in Figure 2.

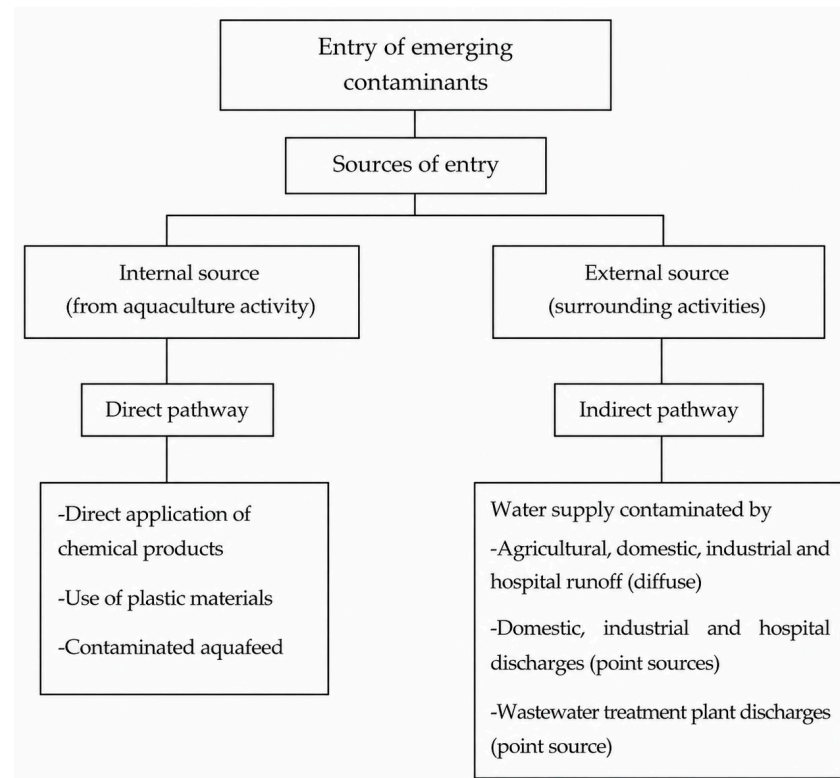


Figure 2. Schematic representation of the sources and entry pathways of Emerging Contaminants (ECs) into aquaculture systems.

The vulnerability of aquaculture systems to emerging contaminants (ECs) varies according to production intensity, water exchange rates, management practices, and proximity to pollution sources. Intensive pond systems are particularly susceptible due to the frequent application of antibiotics, disinfectants, hormones, and pesticides, coupled with limited water renewal, which facilitates the accumulation of contaminants in both the water column and sediments [11,20]. Open-water production systems, including cages and net pens, are directly exposed to contaminants transported from surrounding environments via agricultural run-off, municipal wastewater, industrial discharges, tides, and fluvial flows. Consequently, these systems are more vulnerable to external sources of pollution, despite their higher water exchange rates [11,23]. Recirculating Aquaculture Systems (RAS) substantially reduce the discharge of pollutants into the environment; however, insufficient removal efficiency can lead to the accumulation of antibiotics, microplastics, heavy metals, and antibiotic resistance genes (ARGs) within the recirculating water. Therefore, although RAS are considered environmentally sustainable, continuous monitoring and advanced treatment technologies remain essential to minimise contaminant accumulation [20].

4. Emerging Contaminants in Aquaculture

The most common emerging contaminants in aquaculture are disinfectants, medications, antibiotics, pharmaceutical products, hormones, pesticides and microplastics (Figure 3).

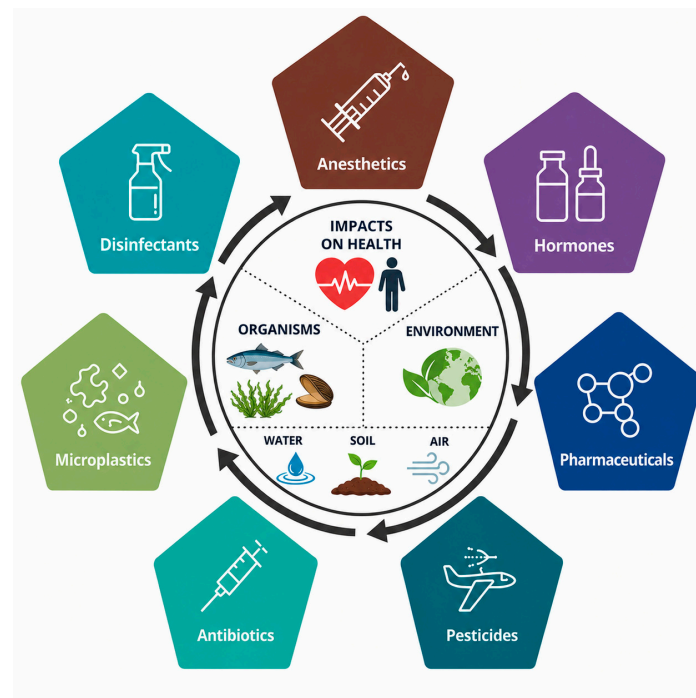


Figure 3. Most common Emerging Contaminants in Aquaculture.

4.1. Disinfectants

Disinfectants are chemical substances used in aquaculture to ensure the biosecurity of farming systems [34]. These products are used to control the proliferation of pathogenic microorganisms in water, on surfaces, in equipment, and in farmed organisms, in order to prevent infectious outbreaks that affect the productivity and health of the system [35–39]. Among the most commonly used disinfectants are hydrogen peroxide (H_2O_2), peracetic acid (PAA), formaldehyde (formalin), and sodium hypochlorite, which have proven effective against bacteria, viruses, fungi, and parasites at different stages of cultivation [39]. Peracetic acid and hydrogen peroxide are preferred in many cases due to their rapid degradation into non-toxic byproducts, such as water and oxygen, minimizing the accumulation of hazardous waste in the aquatic environment [40,41].

Regarding occupational exposure for farm personnel, the handling of these concentrated compounds presents significant risks; for instance, hydrogen peroxide (H_2O_2) can cause respiratory damage and has been associated with an increased risk of developing and exacerbating asthma [42]. H_2O_2 is an irritant affecting the eyes, respiratory tract, and skin, with prolonged exposure potentially leading to chronic respiratory diseases such as bronchitis, pulmonary fibrosis, and an elevated risk of lung cancer [43]. Peracetic acid (PAA) is a highly reactive, peroxide-based chemical substance capable of inducing severe local effects upon direct contact with the eyes, skin, and respiratory pathways [44]. Formaldehyde is classified as a human carcinogen; its exposure may also result in ocular and respiratory irritation, as well as cutaneous sensitisation [45].

Sodium hypochlorite (NaOCl), alongside its derived species such as hypochlorous acid (HOCl) and chlorine gas (Cl_2), are recognised as respiratory irritants. Severe respiratory tract damage caused by NaOCl vapours can precipitate Acute Respiratory Distress Syndrome (ARDS). Studies conducted on animal models have reported severe cutaneous lesions caused by high-concentration NaOCl solutions (>5%). Concentrated NaOCl can severely damage bodily tissues, inducing necrosis (tissue death). Furthermore, high concentrations of NaOCl provoke the breakdown of muscle tissue, known as rhabdomyolysis. HOCl and Cl_2 vapours cause a burning sensation in the oesophagus and cause mucosal

inflammation. Finally, direct inhalation of HOCl, or its formation from the decomposition of NaOCl upon contact with plasma, can destroy red blood cells, resulting in haemolysis [46].

Furthermore, intensive use of these products can negatively impact the beneficial microbiota present in the system, compromising the ecological balance [47]. Therefore, it is essential that their use is based on validated technical parameters, considering the conditions of the cultivation system and the target species, to guarantee both the effectiveness of the treatment and the sustainability of the ecosystem [20,48,49]. Table 1 summarises the primary disinfectants employed in aquaculture, detailing their typical applications, operational advantages, and inherent limitations.

Table 1. Main disinfectants most commonly used in aquaculture [39].

Disinfectant	Compounds	Applications	Advantages	Disadvantages
Chlorinated compounds	Sodium hypochlorite, calcium hypochlorite	Water disinfection. Equipment and facility sanitation. Foot baths.	Broad-spectrum antimicrobial activity. Cost-effective.	Highly toxic to fish and shrimp. Formation of disinfection by products (DBPs). Hazardous to workers.
Peroxides	Hydrogen peroxide	Water disinfection. Control of bacterial and fungal infections. Algacide.	Decomposes into water and oxygen, leaving no harmful residues. Effective against a broad range of microorganisms.	Caustic at high concentrations. Potentially hazardous to workers.
Peracetic acid (PAA)	Peracetic acid	Water disinfection. Control of off-flavors. Treatment of disease outbreaks.	Effective at low concentrations. Decomposes into non-toxic by-products.	Can reduce nitrification rates in biofilters. Potential stress response in fish with frequent use.
Aldehydes	Formaldehyde, glutaraldehyde	Control of parasites and protozoa. Surface disinfection.	Broad-spectrum antimicrobial activity.	Potentially hazardous to workers. Residual toxicity concerns.
Dyes	Malachite green, methylene blue	Treatment of fungal infections. Control of external parasites.	Effective against specific pathogens.	Some are banned due to toxicity and environmental concerns.

4.2. Pharmaceutical Products

Pharmaceutical products in aquaculture comprise a set of chemical substances used for therapeutic, preventive, or physiological management purposes in farmed aquatic organisms [50,51]. These include antibiotics, antiparasitics, anti-inflammatories, anesthetics, reproductive hormones, and other pharmacologically active compounds [52–55]. In aquaculture systems, they are mainly used to control parasitic diseases, modulate growth and reproduction, or reduce stress during handling procedures [54–56].

4.2.1. Anesthetics

The anaesthetic drugs most frequently utilised in fish include tricaine methanesulfonate (MS-222), benzocaine, isoeugenol, metomidate, 2-phenoxyethanol, sodium bicarbonate, and quinaldine [57,58]. They can be administered orally through medicated feed, by immersion in therapeutic baths, or by injection, depending on the product type and the intended health objective [7]. Although these drugs are valuable tools for ensuring health and productivity in aquaculture, their excessive or inappropriate use can lead to serious consequences, such as residues in consumer products, the development of antimicrobial resistance, and environmental contamination arising from untreated wastewater discharges [59,60]. The primary characteristics of the most frequently utilised anaesthetic

agents in aquaculture, including their respective advantages and potential disadvantages associated with their application, are summarised in Table 2.

Table 2. Main anesthetics most commonly used in aquaculture [58].

Anesthetics	Advantages	Disadvantages
Tricaine methanesulfonate (MS-222)	Provides rapid, effective, and reversible anaesthesia. Used for sorting, sampling, tagging, transport, broodstock anaesthesia, gamete collection, blood sampling, vaccination, and invasive surgeries. Inhibits neuronal signal transmission, inducing general anaesthesia and immobilisation.	Potential carcinogenicity. Requires a 21-day withdrawal period before consumption or fish release. Lowers water pH and causes irritation in fish. Induces stress responses. May cause hypoxaemia, hypercapnia, respiratory acidosis, and hyperglycaemia in some species. Presents side effects related to physiological alterations. Caustic at high concentrations. Potentially hazardous to workers.
Metomidate	Induces sedation and hypnosis via GABA receptor regulation. Reduces stress response by inhibiting cortisol production. Diminishes stress associated with handling and capture. Effective for prolonged sedation and anaesthesia in various fish species.	Provides minimal analgesia and immobilisation. Decreases respiration and circulation, leading to hypoxaemia and reduced blood pH. Acts as a stressor in some species. Increases pigmentation and may cause muscle tremors or involuntary movements.
Benzocaine	Effective with rapid induction and adequate recovery. Presents a good safety margin for salmonids. Suitable for short-term tasks such as fish handling and sorting. May reduce circulating cortisol and glucose concentrations under certain conditions.	Powder may cause respiratory irritation during handling. Efficacy depends on fish size and water temperature. Some concentrations may generate stress responses with increased glucose and cortisol. May present prolonged induction times under certain conditions.
Quinaldine	Cost-effective and efficient at low concentrations. Presents low toxicity and rapid recovery in fish. Used for wild fish capture and surgical implantation of transponders. Induction occurs within minutes, and recovery is typically rapid.	May cause tachycardia followed by bradycardia and reduced respiration. May generate elevated stress levels during the process. High concentrations can delay recovery and alter haematological, biochemical, and antioxidant parameters. May cause gill tissue damage at elevated concentrations.
2-Phenoxyethanol	Reduces metabolic activity and mortality during fish transport. Presents short induction time and rapid recovery with limited exposure. Does not alter pH when used in seawater. Widely used in closed fish transport systems.	Physiological stress response may vary depending on duration, concentration, and species. Compliance with safety standards is required due to its toxicity. Prolonged exposure may cause fatigue, drowsiness, and neuropsychological syndrome in handlers.
Propofol	Produces rapid anaesthesia via GABA receptor modulation. Suitable for farm handling, surgeries, and vaccinations. Provides deep, prolonged anaesthesia for complex procedures. Helps maintain ionic and respiratory balance. Protects against peroxidative damage in some fish organs. Causes no genotoxic effects in Nile tilapia at low concentrations.	No specific adverse effects associated with propofol use in fish have been reported.

Despite the generally low toxicity of benzocaine to fish, excessive human exposure to this compound—such as through the consumption of fish with high residual concentrations—can induce severe toxic effects, including arrhythmias, coma, and pulmonary complications. Furthermore, it may trigger allergic reactions such as hypersensitivity and contact dermatitis. In the United States, a tolerance limit of $50 \mu\text{g kg}^{-1}$ has been established for benzocaine residues in fish muscle, with the expectation that residue levels will decline to minimal concentrations within less than 24 h post-treatment [61].

Therefore, their use must be strictly regulated, based on veterinary criteria and respecting the withdrawal periods and maximum residue limits established by health authorities.

4.2.2. Antibiotics

Antibiotics are antimicrobial compounds used in aquaculture to prevent and treat bacterial infections that affect fish and other farmed organisms [62,63]. Among the most commonly used antibiotics are oxytetracycline, florfenicol, enrofloxacin, sulfamethoxazole, sulfadiazine and trimethoprim, which are mostly administered orally through medicated feed [64–69]. Their use is essential in the health management of intensive aquaculture systems, as it allows for the control of bacterial disease outbreaks that could cause high mortality rates and significant economic losses [62,70–73]. However, the excessive, prolonged, or unregulated use of these antimicrobials can generate bacterial resistance, modify the aquatic microbiota, leave residues in fish tissues, and even transfer resistance genes to human pathogens, thus representing both an environmental and public health risk [60,64,74,75]. Antimicrobial resistance (AMR) has emerged as one of the most significant consequences associated with the extensive use of antibiotics in aquaculture. Continuous exposure to antimicrobial residues exerts selective pressure on microbial communities, promoting the proliferation of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs). These resistance determinants can propagate through water, sediments, aquaculture products, and via horizontal gene transfer among bacteria [33].

Currently, approximately 80% of livestock intended for human consumption are administered antibiotics. The use of these pharmaceuticals may leave metabolic residues in the meat, originating either from the antimicrobial agent itself or its secondary metabolites. These substances deposit, accumulate, or are stored within cells, tissues, organs, or edible animal products and may subsequently accumulate in humans over time through regular consumption, thereby increasing the selectivity of multi drug-resistant bacteria towards these pharmaceuticals, which are widely utilised in human healthcare. Residues from antibiotics in food of animal origin represent a significant concern for human health. The consumption of these residues can lead to various disturbances, such as direct toxicity, allergic reactions, and carcinogenic effects (e.g., 4-dedimethylamino-4-oxo-tetracycline) [76]. High doses of florfenicol in tilapia induce reversible renal toxicity and hepatotoxicity [77]. Exposure to enrofloxacin at environmental levels poses a threat to the intestinal and cerebral health of both fish species and humans [78]. Sulfamethoxazole (at $150 \mu\text{g L}^{-1}$) and its combination with trimethoprim demonstrate mild toxicity in fish (*Danio rerio*) following 96 h of exposure, impacting survival, hatching rates, morphological abnormalities, and biomarkers [79].

Furthermore, it has been documented that the release of these emerging contaminants (ECs) into the environment, whether through excretion or uneaten food, can contaminate sediments and surrounding waters, negatively affecting aquatic organisms and associated ecosystems [62,80]. The main impacts associated with antibiotic use, including environmental alterations and potential risks to human health, are presented in Table 3. In consequence their use must be strictly regulated, applied under veterinary supervision, and follow good practices such as respecting withdrawal periods, to guarantee the safety of aquaculture products and reduce ecological impacts [71,81,82].

Table 3. The impact of antibiotics on environmental, animal, and human health [83].

Impact Category	Specific Effects
Human health	Allergy and toxicity issues in consumers and unprotected industry workers. Emergence of resistant bacterial infections in humans.
Animal health	Ingestion of invisible residues in fish, altering intestinal flora and increasing susceptibility to infections. Acute renal failure and pericardial oedema (renal toxicity). Modification and reduction of fish intestinal microbiota diversity, enabling the proliferation of opportunistic bacteria.
Environment	Leaching of antibiotics from unconsumed feed and faeces into the sediment, transported by currents to distant sites. Selective pressure altering the microbial composition of sediment and water.

4.2.3. Hormones

Hormones are chemical substances that regulate essential biological functions in organisms and, in aquaculture, are primarily used to induce sexual maturation, synchronize reproduction, and manipulate the sex of fish for production purposes [57,84–87].

Among the most commonly used are Gonadotropin-Releasing Hormone Analogs (Gn-RHa), human Chorionic Gonadotropin (hCG), and sex steroids such as 17 α -methyltestosterone, used for sex reversal in tilapia and other commercial species [88–90]. Exposure to hormones such as estrone (E1), estriol (E3) and 17 α -ethynylestradiol (EE2) is associated with feminization of male fish, reduced fertility and alteration of the sex ratio in fish populations [91,92]. These hormones can be administered by intramuscular injection, by incorporation into feed, especially during larval stages when sexual differentiation is still developing [93,94]. Although these practices have been shown to improve reproductive efficiency and crop yield, their excessive or uncontrolled use can cause adverse effects such as endocrine disruption, hormone residues in tissues, and environmental pollution, affecting non-target organisms and causing imbalances in aquatic biodiversity [86,95,96]. 17 α -ethynylestradiol (EE2) at concentrations below 0.035 ng L^{−1} has been shown to adversely affect the reproductive performance of fish [97]. These steroid hormones accumulate in the edible tissues of aquatic products consumed by humans, such as fish, and their hormonal residues are resistant to inactivation or thermal elimination. Consequently, the consumption of food of animal origin containing these hormones could expose consumers to additional hormonal effects, impacting physiological processes and public health. The hormone 17 α -methyltestosterone (MT) possesses toxic potential for fish, as it alters enzymatic metabolic pathways and may pose a risk to ecosystems [98]. Oestradiol at a concentration of approximately 1 ng dm^{−3} can induce a distinctive endocrine-disrupting effect in male trout [99]. Therefore, the use of hormones in aquaculture must be subject to strict regulation and veterinary supervision to ensure both productivity and ecological and food safety [86].

4.3. Pesticides

Pesticides are chemical compounds designed to prevent, control, destroy, repel, or attract any biological organism considered as pest, such as insects, crustaceans, parasites, or unwanted aquatic plants [100–102]. In the context of aquaculture, insecticides, piscicides, and molluscicides are primarily used to manage invasive species or vectors that affect production [103,104]. The most commonly used pesticides: fenitrothion, an organophosphate used to eliminate aquatic insects such as *Lethocerus indicus* (water bug), and rotenone, a natural piscicide applied to eradicate unwanted fish in ponds before stocking [105–107].

Application is generally carried out by direct spraying into the water or by controlled dosage based on the pond volume [108]. The extensive use of chemical pesticides poses significant environmental and human health risks (Table 4). Unsupervised use can lead to acute or chronic toxicity in non-target organisms, disruption of aquatic biodiversity, accumulation of hazardous residues in sediment, and risks to human health through the consumption of contaminated fish [109–111]. Furthermore, according to Zhou et al. (2025) [112], as these substances accumulate in the food chain, they threaten higher trophic levels and increase the risk of adverse health consequences, such as acute poisoning, cancer, and neurological disorders.

Table 4. The impact of pesticides on environmental and human health [112].

Impact Category	Domain/System	Specific Effects
Human Health	Critical Systems	Liver cancer, lung cancer, and Diabetes.
	Nervous System	Neurological disorders (Parkinson's, Alzheimer's).
	Fetal Development	Autism, ADHD, and neural tube defects.
	Reproductive System	Infertility and embryonic malformations.
Environment	Specific Organs	Liver injury, bronchitis, asthma, and ocular irritation.
	Water	Residues in drinking water and reduced dissolved oxygen.
	Atmosphere	Persistent aerosols and contribution to climate change.
	Land	Leaching, loss of soil fertility, and crop yield reduction.
	Ecosystem	Mortality of flora/fauna and ecological balance disruption.

4.4. Microplastics

Microplastics (MPs) are plastic particles smaller than 5 mm, resulting from the degradation of larger plastics or intentionally manufactured at that size, these are emerging pollutants that are widely distributed in aquatic ecosystems (marine and freshwater), terrestrial ecosystems and atmospheres [113–115]. In aquaculture, plastics are widely used in the form of nets, pipes, floating rafts, containers, tanks, buoys, feeding systems, and geomembrane liners due to their strength, low cost, and durability [116,117]. However, prolonged exposure to sunlight, saline water, mechanical movement, and physical wear even by microorganisms causes fragmentation, releasing microplastics directly into the aquatic environment [118,119]. Furthermore, these can enter aquaculture systems from external sources, such as urban runoff, domestic wastewater, or contaminated water used for cultivation [120–122]. The main sources and pathways through which microplastics enter aquaculture systems, including inputs from aquaculture infrastructure and external sources, are summarized in Figure 4.

Once present, microplastics can be accidentally ingested by fish and crustaceans, accumulating in their tissues and causing physical damage, triggering inflammatory responses and interfering with digestive, metabolic and immunological processes and reducing reproductive capacity [123–127]. The exposure of organisms to microplastics (MPs) induces physical and chemical toxic effects, including abnormal behaviours, oxidative stress, neurotoxicity, genotoxicity, immunotoxicity, reproductive imbalance, and histopathological effects. However, the severity of these impacts is dependent upon particle size and concentration. Smaller particles are capable of translocating to the intestine and liver, whereas larger particles are confined primarily to the gills and the digestive tract of fish [128].

Microplastics also act as vectors for chemical contaminants and pathogens by adsorbing antibiotics, heavy metals, and resistant bacteria onto their surface [129]. The release of microplastics through wastewater represents an additional contamination route, affecting not only the health of wild aquatic organisms but also water quality, ecosystem services, and potentially human health through the consumption of contaminated products [130–133]. In order to understand the magnitude of this issue, Table 5 synthesises the specific effects and biological systems impacted by microplastic exposure, encompassing the dimensions of human health, marine animal welfare, and the environment.

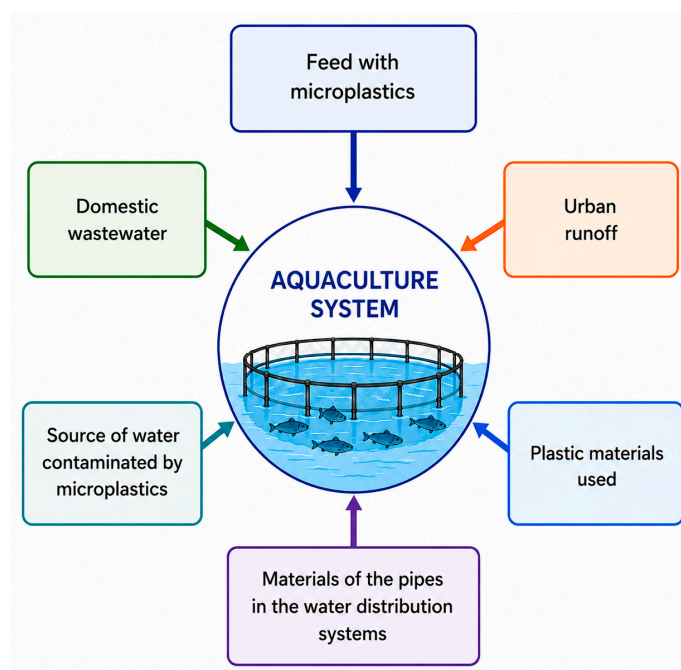


Figure 4. Sources of microplastic entry into aquaculture systems.

Table 5. Classification of specific effects and biological systems impacted by microplastic exposure in humans, marine organisms, and the environment [133].

Impact Category	Domain/System	Specific Effects
Human Health	Respiratory	Chronic respiratory diseases (e.g., asthma and Chronic Obstructive Pulmonary Disease (COPD)).
	Gastrointestinal	Microplastic accumulation in the digestive tract, intestinal wall damage, and alteration of gut microbiota.
	Nervous	Sleep disorders, development of neurodegenerative diseases.
	Metabolic	Development of obesity.
	Endocrine	Increased risk of diabetes.
Animal Health	Physiological	Alteration of physiology.
	Metabolic system	Malnutrition.
	Reproductive system	Interference with reproductive systems.
	Internal anatomy	Damage to internal organs.
	Survival	Mortality.
Environment	Water	Alteration of the food web. Deterioration of aquatic animal health.
	Land	Alteration of soil properties.
		Reduction in water retention capacity. Impact on nutrient cycling.

5. Mitigation Strategies and Degradation Technologies for Emerging Contaminants

The environmental prevalence of Emerging Contaminants (ECs) is exacerbated by the continuous release of novel chemical substances. Due to a lack of systematic monitoring, these constituents often remain undetected until the application of high-resolution analytical methodologies. Accordingly, mitigating ECs within aquaculture systems necessitates a multi-faceted approach, integrating precise source identification with the implementation of high-efficiency treatment technologies. In this context, the characterisation of aquaculture environments—based on the specific typology and provenance of contamination—facilitates the optimisation of control strategies intended to mitigate both ecological risks and human health hazards [134].

Technologically, recirculating aquaculture systems (RAS), in conjunction with biological and physicochemical wastewater treatment methods, have emerged as pivotal tools for reducing ECs loading [20]. Furthermore, sulfate radical-based advanced oxidation processes (SR-AOPs) have gained widespread recognition for their efficacy in degrading persistent ECs through the activation of persulfate (PS) and peroxymonosulfate (PMS) [26]. Moreover, the enforcement of regulatory frameworks aimed at curbing plastic consumption is fundamental to mitigating the generation and sequestration of microplastics (MPs) in aquatic systems, thereby fostering cleaner and more sustainable aquaculture practices [9].

Consequently, Table 6 provides a structured synthesis of the principal ECs reported in aquaculture and the associated ecological and health implications. Furthermore, it outlines current mitigation and remediation strategies alongside evidence-based recommendations for future intervention. This integration enables the identification of occurrence patterns, existing technological constraints, and opportunities for enhancing removal and control frameworks within complex aquatic environments.

Table 6. Emerging Contaminants in aquaculture: environmental impacts, and mitigation strategies.

Reference	Emerging Contaminants (ECs)	Ecological and Health Implications	Mitigation and Remediation Strategies	Recommendations and Future Outlook
Da Mota et al., 2025 [134]	Pharmaceuticals, Personal care products, Pesticides, Hormones, Licit drugs, Caffeine, Bisphenol A.	Decreased O ₂ consumption; Altered swimming patterns; Histopathology; Spermatogenesis inhibition; Cardiac edema; Spinal deformity; antimicrobial resistance.	Advanced Oxidation Processes (AOPs); Biological treatment; Adsorbent materials.	Expand EC research; Continuous monitoring at culture sites; Improve wastewater treatment technologies; Establish ECs legislation.
Su et al., 2025 [135]	Microplastics (MPs); ARGs; Metal resistance genes (MRGs); Antibiotic-resistant bacteria (ARB); Exogenous additives (BPA); Heavy metals.	MPs act as vectors for ARG/MRG propagation; Alteration of bacterial communities; Resistant pathogens (Brucella, Pseudomonas); Health risks via aquatic products; Increased AMR; Potential risk to human health and sustainability.	Monitor MPs and resistance genes; Reduce plastic and antibiotic use; Optimise polymer manufacturing; Improve plastic additive composition.	Evaluate synergistic effects of MP particles and additives; Mitigate ARG propagation; Address dual challenges of MPs and ARGs in aquaculture settings.
Iheanacho et al., 2023 [9]	Microplastics (MPs)	Growth reduction and mortality; Organ accumulation; Oxidative stress; Neurotoxicity; Reproductive, immuno-, and embryotoxicity; Accumulation in gastrointestinal tract.	Improve wastewater treatment plants; Pond water filtration; Fine-mesh filter screening; Substitution of plastics for natural materials (coconut husk, bamboo); Bioremediation via microorganisms/enzymes; Alt protein use; Single-use plastic policies.	Plastic use regulatory policy; Microorganisms for biodegradation; Awareness of plastic pollution; Single-use legislation; Routine evaluation plans; Accidental plastic leak recovery; Prohibit micro-beads.
Ali et al., 2016 [6]	Antibiotics (oxytetracycline, etc.); Pesticides/toxicants (rotenone, etc.); Disinfectants (KmnO ₄ , H ₂ O ₂ , Chlorine); Malachite green; Methylene blue; Feed/water additives (vitamins, probiotics); Zeolite; Liming materials; Yucca extract.	Pathogen antibiotic resistance; Compromised human and animal health; Zooplankton decrease; Moderate/high toxicity for invertebrates and primary producers; Carcinogenic properties.	Probiotic use; Improve water quality and immunological state; Safe alternatives to prophylactic antibiotics.	Additional regulation and impact evaluation; Test efficacy under rigorous conditions; Cost-benefit analysis; Producer technical training; Improve registration and evaluation systems.

Table 6. Cont.

Reference	Emerging Contaminants (ECs)	Ecological and Health Implications	Mitigation and Remediation Strategies	Recommendations and Future Outlook
Liu et al., 2024 [20]	Contaminants (N, P, BOD, TSS); Organic compounds (antibiotics, hormones, pesticides, pharmaceuticals, PCPs); Heavy metals (Hg, Pb, Cd, Cu, Zn); Biological contaminants (bacteria, viruses, parasites); Metabolic waste.	Occupational risks; Food security and public health hazards; Environmental damage (eutrophication, toxicity, resistance).	Application of biological and physicochemical methods; Recirculating Aquaculture Systems (RAS).	Establish robust legislation for the aquaculture industry; Standardise wastewater discharge standards.
Hidayati et al., 2021 [23]	Analgesics (paracetamol) and Antibiotics (trimethoprim, oxytetracycline, sulfamethoxazole).	OTC poses high risks for algae; ACM, TMP, and SMX present insignificant risks for algae, invertebrates, and fish.		Improve pharmaceutical waste management; Monitor concentrations in water bodies; Implement strict antibiotic regulations; Sustainable aquaculture practices; Regulate sulfamethoxazole use.
Xie et al., 2024 [136]	Antibiotics; Microplastics (MPs); ARGs; Heavy metals and pathogens.	MPs act as vectors for food web transfer; MPs lead to ARGs under selective pressure; Horizontal gene transfer (HGT) facilitated by bacterial communities; Ecological and health risks.	Membrane technologies; Coagulation; Advanced Oxidation Processes (AOPs); Ecological treatment technology development.	Research on ecological treatment of ECs in aquaculture wastewater; Develop integrated systems for effective treatment.
Zhang, 2024 [22]	Pharmaceuticals; PCPs; Heavy metals; Pesticides; Microplastics; Endocrine disruptors (hormones); Nanomaterials; Biological contaminants; Drug residues; E1, E3, EE2; Mercury.	Endocrine disruption; Bioaccumulation; Fish feminisation; Fertility reduction; Sex ratio alteration; Growth inhibition; Disease susceptibility; Biodiversity loss; Human health risks via seafood; Neurological issues; Food web chemical interactions.	Advanced treatment technologies; Membrane filtration; Adsorption via biochar; Biological treatment (microalgae); Enzyme/biosensor biodegradation; Effect-Based Methods (EBMs).	Global adaptive policies; Long-term monitoring; Strict regulatory implementation; Awareness campaigns; Incentives for Green Chemistry; “Cradle-to-grave” normative design.
Sun et al., 2025 [137]	Phenols (prevalent in water near activities); Antibiotics (predominant in terrestrial farms)	Bioaccumulation in aquatic organisms; Ecological risks and impact on biodiversity.	Risk assessment (identification and quantification); Sustainable agricultural practices; Adequate effluent treatment.	Continuous monitoring; Surveillance programmes for ECs detection; Regulatory policies for potentially toxic substances in agriculture.

6. Future Perspectives

Future research should prioritise the implementation of long-term monitoring programmes capable of assessing the occurrence, seasonal variability, and chronic exposure to emerging contaminants across diverse aquaculture systems. Standardised analytical methodologies and harmonised monitoring protocols are required to improve data comparability across regions and production systems.

Further research is also necessitated to understand the combined toxicity of contaminant mixtures, the environmental behaviour of transformation products generated during treatment processes, and the bioaccumulation and trophic transfer of contaminants throughout aquatic food webs. Greater attention must also be directed towards antimicrobial resistance, particularly regarding the interactions between antibiotics, microplastics, heavy metals, and antibiotic resistance genes (ARGs) within aquaculture environments.

From a technological perspective, future efforts should focus on enhancing the efficiency of wastewater treatment through advanced oxidation processes (AOPs), membrane filtration, adsorption materials, biological treatments, and integrated Recirculating Aquaculture Systems (RAS). The development of biodegradable materials to substitute conventional

plastics, coupled with more stringent regulations governing the use of chemical products and wastewater discharge, will also contribute to reducing contaminant emissions and improving the environmental sustainability of aquaculture.

7. Conclusions

The prevalence of Emerging Contaminants (ECs) within aquaculture systems presents a multifaceted environmental challenge, with profound implications for ecosystem integrity, biodiversity, and public health. This review demonstrates that ECs—originating from both intrinsic aquaculture practices and extrinsic anthropogenic sources—persistently sequester within water, sediments, and aquatic biota, subsequently undergoing trophic transfer throughout the food web. Furthermore, contaminants such as disinfectants, pharmaceuticals, pesticides, and microplastics do not only exert toxicological effects on aquatic species but also precipitate the proliferation of antimicrobial resistance and a broader ecological impact.

Despite advancements in detection and remediation technologies, including Recirculating Aquaculture Systems (RAS) and Advanced Oxidation Processes (AOPs), significant constraints remain regarding cost-effectiveness, scalability, and regulatory implementation. Consequently, addressing the impact of ECs necessitates interdisciplinary frameworks that integrate continuous monitoring, stringent regulatory oversight, a reduction in the use of hazardous substances, and the adoption of sustainable treatment methodologies.

This review provides a comprehensive synthesis of the sources, exposure pathways, impacts, and mitigation strategies associated with ECs in aquaculture, establishing a robust scientific foundation for future research and evidence-based policy-making. The implementation of these integrated strategies is imperative to ensure the long-term sustainability of aquaculture systems while safeguarding environmental quality and human health.

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Abbreviation

The following abbreviations are used in this manuscript:

ECs Emerging contaminants

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