Review

New contaminants in aquaculture and livestock waste: from environmental fate to mitigation technologies

Shuyu Sun[1,2#], Jingrui Deng[1,2#], Jingyi Li[1,3], Guixue Song[4], Siyuan Ye[5] and Qigui Niu[1,3*]

Abstract

The intensive development of large-scale livestock and aquaculture industries has underpinned global food security. However, the extensive use of veterinary drugs, feed additives, and other related inputs driven by this industrial expansion has led to the continuous accumulation of new contaminants (NCs) in farming waste, such as antibiotics, antibiotic resistance genes (ARGs), antibiotic-resistant bacteria (ARB), endocrine-disrupting compounds (EDCs), and micro- and nano-plastics (MNPs). These pollutants undergo multi-media migration, transformation, and food chain transmission, posing potential threats to ecosystems and human health. This review systematically summarizes the sources and occurrence characteristics of NCs in different types of farming waste, with a focus on their environmental fate and multi-media transport behavior. It further elaborates on the ecological risks arising from the bioaccumulation of these contaminants. Additionally, the removal efficiencies of physical, chemical, biological, and combined control technologies for NCs are evaluated. Emphasis is placed on the importance of analyzing composite pollution mechanisms, establishing precise risk modeling, and implementing integrated full chain strategies encompassing 'source substitution-process interception-end treatment'. Future research should prioritize the mechanistic understanding of combined pollution, accurate risk assessment, and intelligent management to provide a scientific basis for promoting the green transformation of aquaculture and safeguarding watershed environmental health.

Highlights

- New contaminant profiles in livestock and aquaculture waste are characterized.
- The environmental fate of new contaminants in farming waste is elucidated.
- Ecological risk transmission pathways and assessment methods are reviewed.
- The roles of source reduction for new contaminants are evaluated.
- Combined removal technologies for new contaminants are summarized.

\# Authors contributed equally: Shuyu Sun and Jingrui Deng

* Correspondence: Qigui Niu (niuqg@sdu.edu.cn)

Full list of author information is available at the end of the article.

Graphical abstract
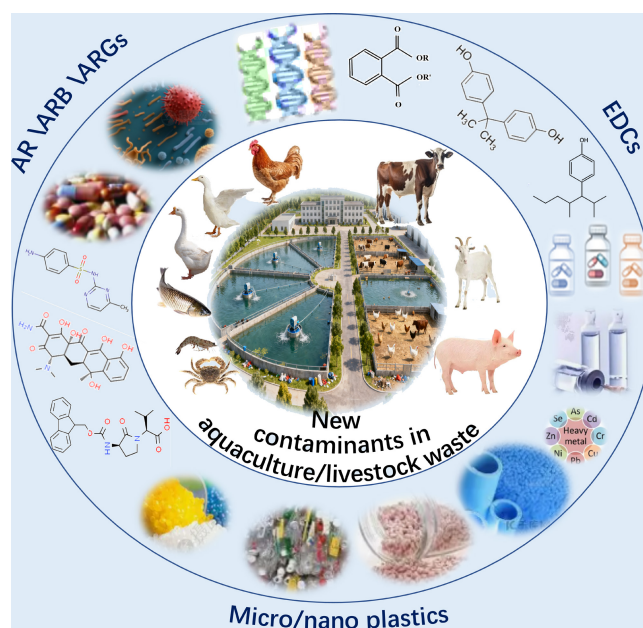
Introduction

Large-scale and high-density livestock farming and aquaculture, as crucial components of modern agriculture, have become a core pillar for ensuring global food security and promoting economic development. According to the Food and Agriculture Organization (FAO) of the United Nations, the global annual meat production is projected to increase from the current 228 million tonnes to 463 million tonnes. By 2050, with the annual output of poultry expected to exceed 37 billion[1], the stock of cattle will rise from 1.5 billion to 2.6 billion, the stock of goats and sheep will increase from 1.7 billion to 2.7 billion[2], and the output of aquaculture reach 109 million tonnes[3]. However, while providing abundant animal protein products and creating substantial economic value, the industry's sustainable development path has become a global focus due to its massive resource demand and pollutant emissions.

Currently, the environmental challenges posed by breeding wastes are shifting from conventional organic pollution to new contaminants (NCs) represented by persistent organic pollutants (POPs), endocrine-disrupting compounds (EDCs), microplastics, and antibiotics. Owing to their concealed nature and complex risks, these substances have become a core challenge and frontier area in environmental governance[4,5]. To date, reported NCs in breeding wastes are mainly categorized into three types: (1) Antibiotic resistance (AR), antibiotic-resistant bacteria (ARB), and antibiotic resistance genes (ARGs). Excessive use of antibiotics in breeding (such as fluoroquinolones, tetracyclines) cannot be fully metabolized by animals and enter the environment with manure. They further induce bacteria to produce ARGs and generate a large number of ARB, exacerbating the spread of antimicrobial resistance[6]. (2) EDCs, including exogenous hormones added to feed (such as steroid hormones)[7], phthalic acid esters (PAEs) released from plastic equipment[8], per- and polyfluoroalkyl substances (PFAS)[9], and veterinary drugs (such as avermectins)[10] generated during production. These compounds can interfere with the endocrine functions of aquatic and terrestrial organisms. (3) Micro- and nano-plastics

(MNPs). These particles are primarily derived from microplastics formed by the aging and fragmentation of plastic mulch films, feed packaging, and pipelines, as well as nano-additives in feed (such as nanopreparations of trace elements). They are recalcitrant, prone to enrichment in the environment, and form complex combined pollution as carriers[11].

The core risk of NCs in the breeding environment stems from their environmental persistence, bioaccumulation potential, and food chain magnification effect, posing long-term threats to ecosystems and public health. Long-term exposure is closely associated with various health issues, including cancer, endocrine disorders, immunosuppression, and developmental abnormalities[12]. These pollutants diffuse extensively into environmental media like water, soil, and air through pathways such as manure discharge, organic fertilizer application, and runoff. More critically, NCs possess complex interactions, which can induce additive or synergistic toxicity in the environment[13]. Furthermore, they are resistant to effective removal through natural attenuation and conventional treatment processes. Consequently, these substances persist and ultimately accumulate in soils, sediments, and aquatic food chains, affecting organisms from invertebrates to humans[14]. This dynamic exemplifies the 'One Health' framework, which highlights the interconnected health risks across humans, animals, and the environment (Fig. 1).

Although the potential risks of NCs have attracted widespread attention, notable gaps remain in current research on aquaculture and livestock wastes. Firstly, there is a lack of systematic understanding regarding the sources and occurrence, synergistic and combined effects, as well as ecological risk transmission of various NCs in these wastes. The key processes of their multi-media migration and transformation, along with the driving mechanisms of synergistic control, remain unclear. Additionally, traditional risk assessment frameworks struggle to effectively quantify the combined risks posed by these contaminants to ecosystems and human health under conditions of low concentrations and long-term exposure.

This review aims to systematically synthesize the occurrence characteristics, environmental fate and behavior, ecological and health
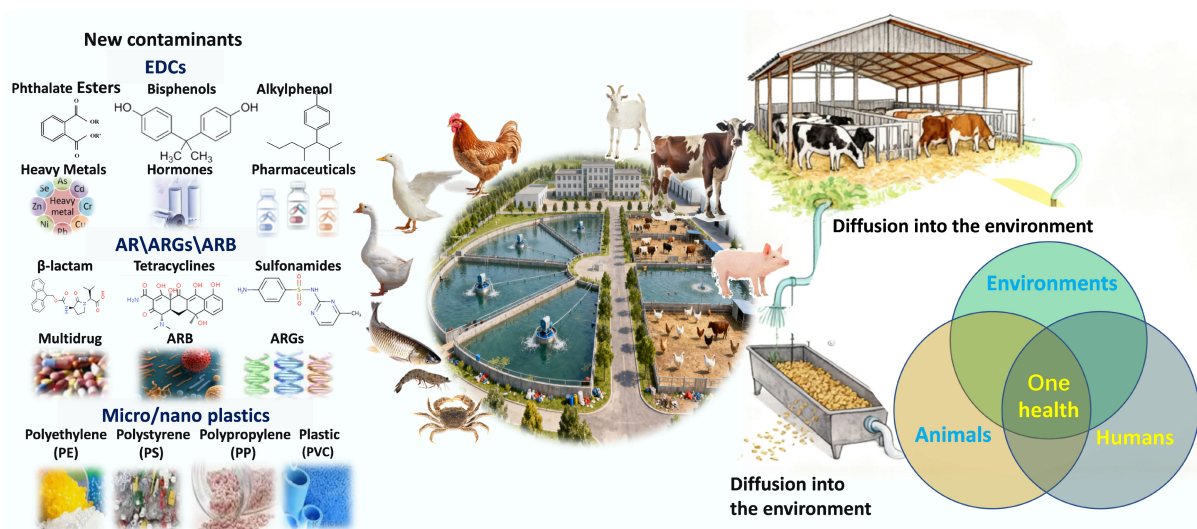
Fig. 1 New contaminants in aquaculture and livestock waste.

risks, as well as systematic control strategies of NCs in aquaculture and livestock wastes. It provides a theoretical basis for the formulation of future research directions and management strategies, thereby promoting the development of the breeding industry toward a more environmentally friendly and sustainable path.

Occurrence characteristics and source apportionment of NCs in breeding wastes

Typical NCs in breeding wastes

EDCs

EDCs in wastes from large-scale intensive farming are extrinsic chemical substances that target nuclear receptors to interfere with the endocrine systems of organisms, posing potential threats to ecosystems and human health[15]. Originating from diverse sources, EDCs mainly include hormones, alkylphenols, polyhalogenated compounds, bisphenol A (BPA), PAEs, pharmaceuticals, and pesticides[16–18]. During the farming process, EDCs often enter the environment through pathways such as feed additives, plastic facilities, and manure application to farmland, and accumulate in water bodies, soil, and organisms.

In aquaculture and livestock farming systems, EDCs enter the waste stream through multiple pathways, including feed additives, plastic equipment, water systems, disinfectants, and manure application, ultimately accumulating in water, soil, and biota (Fig. 2)[19–24].

Alkylphenol ethoxylates (APEs), commonly found in detergents, paints, and pesticides, represent a major class of estrogenic compounds in farming wastes[19]. BPA and its substitutes (Bisphenol S [BPS] and Bisphenol F [BPF]), widely used in feed packaging, drinking pipes, and mulching films, can be ingested by animals, accumulate in adipose tissues, and transfer into meat, eggs, and milk[20]. While PAEs are commonly used as plasticizers, they can easily leach from farming equipment such as feed containers, nets, and tubing, especially when exposed to high temperatures, humidity, or ultraviolet radiation (UV) light[21]. PFAS are extremely persistent in the environment due to their stable C–F bonds, which resist biological, photolytic, and hydrolytic degradation[22,23]. Fishmeal has been identified as a significant source of PFAS in aquatic species and related products, such as farmed Atlantic salmon[24].

There are significant differences in the enrichment levels of EDCs among different farming systems. The concentration of EDCs in livestock and poultry manure reaches the microgram per kilogram level; for example, the total estrogen content in chicken manure is 40.08 μg/kg[25], and the average BPA content in cow manure is 11.7 μg/kg[26]. In contrast, the concentration in aquaculture organisms is at the nanogram per gram level; for instance, the 4-nonylphenol content in fish ranges from 1.39 to 158.35 ng/g[27]. These differences are closely related to the characteristics of farming media and the migration laws of pollutants.

AR, ARGs, and ARB

The extensive use of antibiotics in livestock, poultry, and aquaculture has given rise to a series of environmental and health issues. It is shown that the antimicrobial consumption per kilogram of product in global livestock production is 59.6 mg for cattle, 35.4 mg for chickens, and 173.1 mg for swine, while that in aquaculture is as high as 208 mg[28]. It is projected that global antimicrobial consumption will increase to approximately 104,000 tonnes by 2030[28]. In addition to directly causing antibiotic residues, of greater concern is that the continuous discharge of antibiotics from breeding wastes promotes the proliferation and spread of ARB and ARGs. Despite the introduction of restrictive policies in many countries, antibiotic residues are still commonly detected in breeding environments, highlighting the persistence and concealment of pollution[29,30].

ARB enter the environment through excretion, serving as viable carriers for ARGs dissemination and significantly increasing human exposure risks (Table 1)[31]. Resistance genes spread primarily through vertical gene transfer and horizontal gene transfer (HGT)[30,32], with their transmission efficiency significantly increased via conjugation, transformation, and other mechanisms[33]. The concentration of common ARB (such as *Escherichia coli*, *Klebsiella pneumoniae*, *Enterococcus* spp.) in swine manure can reach 10^8 CFU/g[34], exacerbating the risk of antimicrobial resistance spread.

MNPs

MNPs in breeding wastes pose dual threats to ecosystems and human health[35], with their risks stemming from the intrinsic toxicity of the particles themselves and the synergistic effects as pollutant carriers[36]. On the one hand, MNPs are prone to causing physical damage triggered by biological uptake, and simultaneously release contained
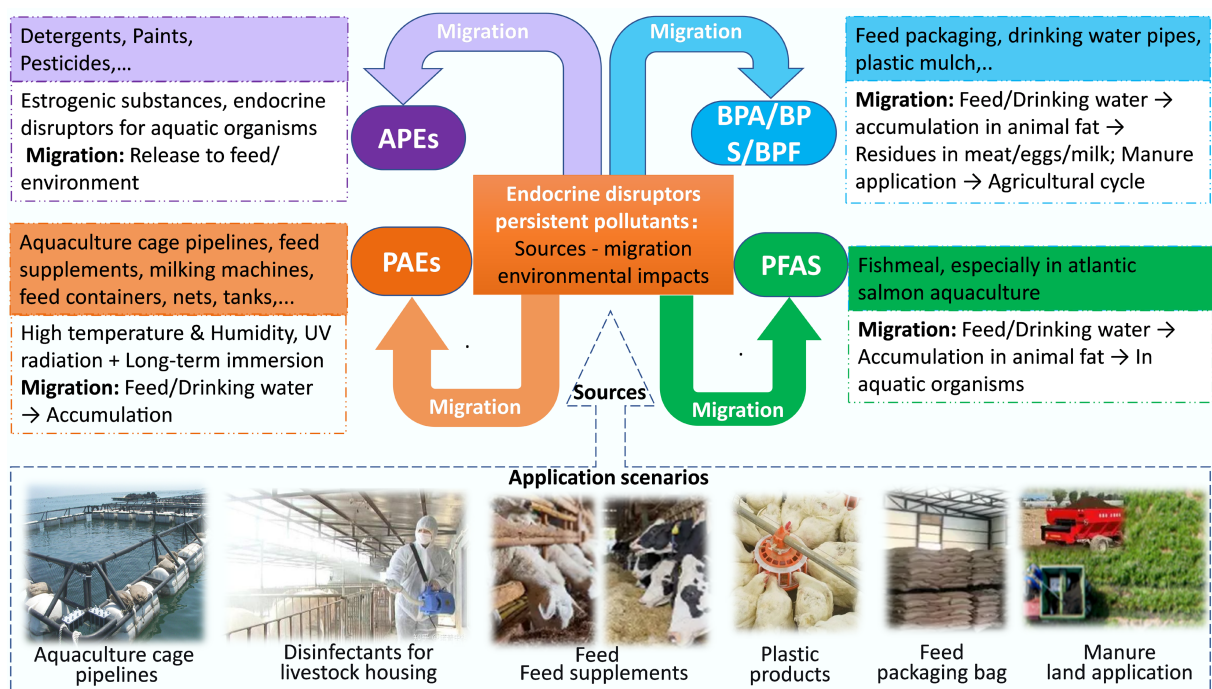
Fig. 2 Sources of EDCs in aquaculture and livestock waste[19–24].

Table 1 Distribution and characteristics of AR, ARB, and ARGs

Category	Antibiotic class/ARB type	Main associated ARGs	Main detected strains/genera	Typical abundance and variation trends in the environment
Antibiotics and ARGs	Tetracyclines	*tetA*, *tetB*, *tetM*, *tetO*, *tetW*, etc.	Widely present in gut microbiota (*Escherichia coli*, *Enterococcus* spp.) and the environment	High initial abundance in manure; reduced after aerobic composting, but genes may persist
	Sulfonamides	*sul1*, *sul2*	Widely present in gut microbiota and the environment	High environmental persistence; marker for fecal pollution; may remain after treatment
	β-lactam	*bla*TEM, *bla*CTX-M, *bla*SHV, *bla*KPC, *bla*OXA-48, *mec*A, etc.	Carbapenem-resistant Enterobacterales (CR-E), ESBL-producing *E. coli/Klebsiella pneumoniae*, and ampicillin-resistant *E. coli*	High abundance in hospitals and breeding wastewater; many strains and genes remain detectable in treated effluents, posing high risks
	MLSB	*erm*B, *erm*C, *lnu*E, *str*A, etc.	Gram-positive bacteria (such as *Enterococcus* spp.)	Composting reduces viable bacterial counts, but genes may persist
	Aminoglycoside	*aac*, *aad*A, *aad*B, etc.	Enterobacterales, *Enterococcus* spp., etc.	Common in multidrug-resistant strains
	FCA	*qnr*S, *aac*(6')-Ib-cr, *flo*R, *cat*, etc.	*E. coli*, *Salmonella* spp., etc.	Prevalent in breeding environment, selection pressure from florfenicol and quinolones
	Colistin	*mcr*-1, *mcr*-2, etc.	*E. coli*, *Salmonella* spp., etc.	A concerning resistance to the last-resort antibiotic
	Vancomycin	*van*A, *van*B, etc.	*Enterococcus* spp.	Important hospital-acquired resistant bacteria; potential detection risk in wastewater
	Multidrug	*acr*A, *acr*B, *mex*B, *oqx*A, etc.	Multidrug-resistant (MDR) *E. coli*, MDR *Enterococcus* spp.	These efflux pump genes promote bacterial multidrug resistance, making them difficult to eliminate
ARB	Enterobacterales	*bla*KPC, *bla*OXA-48, etc.	*E. coli*, *Klebsiella pneumoniae*	Extremely high risk; detectable after treatment
	ESBL-producing *E. coli/Klebsiella pneumoniae*	*bla*CTX-M-15, *bla*CTX-M-14, etc.	*E. coli*, *Klebsiella pneumoniae*	Common in medical and breeding environments; remains detectable in treated effluents
	Ampicillin-resistant *E. coli*	*bla*TEM-1, etc.	*E. coli*	High initial count (~10^8 CFU/g); significantly reduced after aerobic composting
	Multidrug-resistant (MDR) *E. coli/Enterococcus* spp.	A combination of multiple genes mentioned above	*E. coli*, *Enterococcus* spp.	High proportion in hospital wastewater; remain detectable in treated effluents
	ARB in aquaculture environments	Genes associated with β-lactams, macrolides, tetracyclines, sulfonamides, etc.	*Enterococcus* spp., *Morganella* spp., *Klebsiella pneumoniae*, *Serratia* spp., etc.	Widely distributed across all sites in the breeding environment; may cause cross-contamination during processing

additives such as plasticizers and flame retardants, leading to direct ecotoxicity. On the other hand, due to their hydrophobic properties, MNPs strongly adsorb persistent pollutants, heavy metals, and antibiotics in the environment, forming combined pollution aggregates[36]. When these pollutant-loaded particles are ingested by organisms, the pollutants are transiently released in the gastrointestinal tract,

producing a 'Trojan horse' effect that significantly enhances their bio-availability and combined toxicity[37]. Notably, common polymers such as polypropylene (PP) and polyethylene (PE) are widely present in aquaculture and livestock feed and facilities[38], continuously releasing additives posing health hazards like plasticizers, flame retardants, and BPA[39]. Therefore, MNPs possess a dual identity as both 'pollutants' and

'carriers', and future risk assessments should focus on their combined ecological effects under long-term low-dose exposure.

NCs in different types of breeding wastes

Contaminant profiles in livestock and poultry breeding wastes

As shown in Table 2, livestock and poultry breeding wastes are important sources of NCs, with their pollutant profiles closely linked to breeding species[40]. Extensive use of antibiotics such as tetracyclines, β-lactams, and sulfonamides in livestock farming and aquaculture has made livestock and poultry manure a major source of ARGs and ARB.

The abundance (up to 10^{11} copies/g) and diversity of ARGs in swine and chicken manure are generally higher than those in cattle and sheep manure, which is consistent with the more intensive antibiotic application patterns in swine[41–43] and chicken farming[41,44,45]. Dominant ARG types vary across different breeding systems: tetracycline resistance genes (such as *tetM*, *tetW*) predominate in swine and chicken farms, while cattle farms show a significant association with macrolide resistance genes and the *sul1* gene[45–47].

Notably, sulfonamide resistance genes (*sul1*, *sul2*) have become common contaminants in groundwater around breeding farms due to their strong environmental mobility[48], indicating persistent environmental and health risks[49].

Microplastics in livestock and poultry manure exhibit significant interspecific differences in abundance: the highest concentration is found in swine manure ($9.02 \times 10^2 \pm 1.29 \times 10^3$ particles/kg), followed by layer chicken manure ($6.67 \times 10^2 \pm 9.90 \times 10^2$ particles/kg), and the lowest in dairy cow manure ($7.40 \times 10^1 \pm 1.29 \times 10^2$ particles/kg)[50]. These microplastics are mainly composed of polypropylene and polyethylene, primarily derived from feed and its packaging.

Regarding EDCs, PFAS concentrations in poultry manure are generally low (0.66 μg/kg), significantly lower than those in municipal and industrial wastes (220 μg/kg)[51]. In contrast, concentrations of BPA and PAEs vary by species and feeding patterns, with higher levels detected in intensive breeding farms, reflecting plastic product exposure as a major source[52,53].

Characteristic profiles of contaminants in aquaculture

Aquaculture represents another significant industry alongside livestock farming. As the fastest-growing food industry globally[62,63], the rapid increase in aquaculture production and consumption has been

Table 2 Comparison of concentrations of NCs across different livestock and poultry farming systems

Species category	Types	Medium	Main types	Concentration (ww)	Detection rate	Ref.
Chicken	Antibiotic residues	Manure, breeding wastewater	Tetracyclines, fluoroquinolones, sulfonamides, cephalosporins	Tetracyclines: highest (9.7×10^3–3.2×10^4 μg/kg); Fluoroquinolones: 430.7 μg/kg	Core antibiotics: 100%; Sulfonamides: 35%	[41,42]
	ARGs	Manure, breeding wastewater	*tet* family (*tetO*/*tetW*), sul family (*sul1*/*sul2*), bla family	Total ARG abundance: 10^6–10^{11} copies/g; *tet* family: 10^6–10^8 copies/g;	100%	[41,45]
	ECDs	Manure	E1, 17β-E2, E3	E1: 28.72 μg/kg; 17β-E2: 3.95 μg/kg; E3: 7.4 μg/kg	Overall detection rate: 71.42%	[25]
	MPs	Manure, chicken farm environment	PE, PS, PET, Nylon Fibers, PP	$6.67 \times 10^2 \pm 9.90 \times 10^2$ particles/kg	50%–100%	[50]
Swine	Antibiotic residues	Manure, swine farm wastewater	Tetracyclines, fluoroquinolones, sulfonamides	Tetracyclines: 8.9×10^3–3.0×10^4 μg/kg; Fluoroquinolones: 1,670.58–7,832 μg/kg; Sulfonamides: 148.3 μg/kg	Tetracyclines: 90%; Sulfonamides: 33%	[41–43]
	ARGs	Manure, swine farm wastewater	*tet* family, *sul* family, *ermB*	Total ARG abundance: 10^7–10^9 copies/g; *tet* family: 10^6–10^8 copies/g; Swine farm wastewater: 10^6–10^{12} copies/mL	100%	[40,45]
	ARB	Manure	ESBL-producing *Escherichia coli* (*E. coli*), LA-MRSA	ESBL-producing *Escherichia coli*: 1.8×10^3–5.2×10^3 CFU/g; LA-MRSA: 1.2×10^2–3.5×10^2 CFU/g	42%–60%; 25%–38%	[40,45]
	EDCs	Breeding wastewater, manure	Breeding wastewater: natural estrogens: 17α-E2, 17β-E2, E1 Manure: E1	Breeding wastewater: 17α-E2: 10.9 ng/L, 17β-E2: 8.0 ng/L, E1: 27.3 ng/L, Total estrogens: 46.2 ng/L; Manure: E1: ND ~21 μg/kg	Breeding Wastewater: 17α-E2, 17β-E2, E1: 100%;	[25,54]
	MPs	Manure, intestinal tract, lung tissue	PP, PE, PR, PES, PA, PET	Manure: $9.02 \times 10^2 \pm 1.29 \times 10^3$ particles/kg (17.6% < 0.5 mm); Intestinal tract: 9.6×10^3 particles/kg; Lung tissue: 1.8×10^5 particles/kg	Manure: 100%; Tissues: 90%	[50,55,56]
Cow	Antibiotic residues	Manure, rumen contents, cow farm wastewater	Tetracyclines, fluoroquinolones, sulfonamides, macrolides	Tetracyclines: 30.07–51.36 μg/kg; Fluoroquinolones: 77.19 μg/kg; Sulfonamides: 9.26 μg/kg	Core antibiotics: 75%–90%	[41–43]
	ARGs	Manure, rumen contents	*tet* family, *ermB*, *sul1*, *ermB*, *bla*CTX-M	Total ARG abundance: 10^5–10^8 copies/g; *ermB*: 10^5–10^6 copies/g	95%	[45–47]
	EDCs	Breeding Wastewater, manure	Natural estrogens: 17α-E2, Breeding wastewater:17β-E2, E1 Manure: E3, 17β-E2, BPA	Breeding Wastewater:17α-E2: 19–1,028 ng/L, 17β-E2: 29–289 ng/L, E1: 41–3,057 ng/L, Total estrogens: 60 – over 4,000 ng/L; Manure: E3: ND–240.9 μg/kg, 17β-E2: ND–88.3 μg/kg, BPA: ND–33.3 μg/kg	17α-E2, 17β-E2, E1: 85.7%; E3: 20%, 17β-E2: 80%, BPA:50%	[26,54,57]
	MPs	Manure	PE, PP, PET, PVC	$7.40 \times 10^1 \pm 1.29 \times 10^2$ particles/kg;	Manure: 75%–100%; Rumen: 80%	[55,58,59]
Sheep	ARGs	Manure, rumen contents	*tet* family (*tetO*/*tetQ*/*tetW*), *ermF*	Total ARG abundance: 10^5–10^7 copies/g; *tet* family: 10^4–10^6 copies/g	100%	[45,60,61]
	ARB	Manure	*Enterococcus* spp.	1.2×10^3–3.6×10^3 CFU/g	95%	
	EDCs	Breeding wastewater	Natural estrogens: 17α-E2, 17β-E2, E1	17α-E2: 172 ng/L, 17β-E2: 47.1 ng/L, E1: 157 ng/L, Total estrogens: 376.1 ng/L;	17α-E2, 17β-E2, E1: 100%;	[54]
	MPs	Manure, intestinal tract	PE (Low-Density), PP, PET, PA	Manure: 997±971 particles/kg; Intestinal tract: 10^2–10^3 particles/kg	Manure: 92%; Intestinal tract: 100%	[55,58]

PR: Polyester; ARGs: Antibiotic Resistance Genes; ARB: Antibiotic-Resistant Bacteria; EDCs: Endocrine-Disrupting Compounds; MPs/NPs: Microplastics/Nanoplastics; PE: Polyethylene; PS: Polystyrene; PET: Polyethylene Terephthalate; PP: Polypropylene; PVC: Polyvinyl Chloride; PA: Polyamide; PES: Polyethersulfone; LDPE: Low-Density Polyethylene; ESBL: Extended-Spectrum β-Lactamase; LA-MRSA: Livestock-Associated Methicillin-Resistant Staphylococcus aureus; 17α-E2: 17α-estradiol; 17β-E2: 17β-estradiol; E1: Estrone.

accompanied by the emergence of pollutants and health risks[64]. The issue of combined pollution associated with its rapid development has become increasingly prominent, forming a unique 'aquaculture-characteristic pollution profile'[65]. This pollution profile mainly includes heavy metals, antibiotics, POPs, and pathogenic microorganisms. Among these, the concentrations of heavy metals such as copper, zinc, lead, and metalloids like arsenic in aquaculture water bodies must be strictly controlled within limit values. Pathogens, including enterotoxigenic *Escherichia coli*, *Salmonella* spp., *Campylobacter* spp., *Shigella* spp., and *Vibrio* spp., may threaten human health through fish as a vector[62]. In addition, wastewater discharged from aquaculture is rich in nutrients such as nitrogen and phosphorus, as well as organic matter, which can easily induce eutrophication and hypoxia in water bodies and damage the benthic ecosystem.

Even more concerning is the fact that farmed aquatic products have become a significant route through which NCs are transmitted to humans. As shown in Table 3, residues of antibiotics such as erythromycin (ETM), ciprofloxacin (CFX), norfloxacin (NOR), and sulfamethoxazole (SMX) have repeatedly been found to exceed standard limits in aquatic products[66], and a high detection rate of antibiotics has also been reported in aquaculture wastewater[67–70].

Regarding PFAS pollution, significant variations in bioaccumulation have been observed among different aquatic products. For instance, the concentration of Σ_{11}PFAS in mussels can reach 4.83–6.43 ng/g[71], which is significantly higher than that in abalones, oysters, and lobsters. Most farmed fish show low pollution levels (mean concentration range: 0.06–1.5 ng/g)[72]. Due to endogenous emissions and feed additions, effluents from aquaculture farms also contain EDCs such as steroid hormones; although their concentrations are relatively low, their impacts cannot be ignored[73].

Microplastics are found in both aquaculture water and seawater[74,75]. The microplastic concentrations in the farming environments of crabs and crayfish (233–733 particles/m^3) are generally slightly higher than those in fish (83–550 particles/m^3), attributable to increased exposure from the use of plastic enclosures[76]. The microplastic content in various aquatic organisms is higher than that in natural water bodies[77,78], demonstrating their strong ability to accumulate microplastics.

Environmental fate mechanisms of NCs in livestock waste

Multimedia migration and environmental persistence

The environmental behavior of NCs in different farming systems determines their ultimate fate and ecological risks[79]. Core processes include environmental transport and persistence, bioaccumulation and trophic transfer, transformation and activation[80].

In terms of environmental transport and persistence, compounds such as BPA and phthalates demonstrate persistent existence due to continuous input despite their biodegradable nature, while halogenated compounds like polybrominated diphenyl ethers (PBDEs) can persist long-term and undergo long-range transport owing to their high chemical stability. During bioaccumulation, hydrophobic EDCs are prone to accumulating in organisms due to their high lipophilicity[81,82] and can undergo biomagnification through the food chain, ultimately posing human exposure risks via aquatic products[83]. Furthermore, contaminants that settle with particulate matter may be re-released into the water column due to bioturbation by benthic organisms, thereby elevating ecological risks[84].

Table 3 Comparison of concentrations of new contaminants across different aquaculture types

Species category	Pollutant type	Sample type	Main types	Concentration	Ref.
Tilapia	Antibiotics	Pond water	TMP, CFX, etc.	94.30 ± 11.56 ng/L	[68]
		Organism tissues	SDZ, SDM, SQX, CFX, TC, ETM, CTM, RTM	17.20 ± 1.51 ng/g ww	
Olive flounder	Antibiotics	Aquaculture effluent	AMX, FLO, OXO, OTC	AMX: 39–1,145 ng/L	[67]
				FLO: 22–1,448 ng/L	
				OXO: 31–992 ng/L	
				OTC: 33–9,935 ng/L	
Grass carp	Antibiotics	Pond water	ETM-H$_2$O, SMX, LIN, etc.	222–1,792 ng/L	[69]
Pacific white shrimp	Antibiotics	Aquaculture tailwater	FLO, ENR, SMX, TMP, etc.	8,600–29,000 ng/L	[70]
		Organism tissues	TMP, ENR, SMX, CIP, FLO, TPL	0.072–11.8 µg/kg ww	
Salmon	EDCs	Aquaculture effluent	Estrone, testosterone, androstenedione	About 1–2 ng/L	[73]
Eel	EDCs	Organism tissues	PFAS	3.3–67 ng/g ww	[72]
Mussel, oyster, abalone, lobster	EDCs	Organism tissues (abalone)	PFAS	0.12–0.49 ng/g ww	[71]
		Organism tissues (mussel)	PFAS	4.83–6.43 ng/g ww	
		Organism tissues (oyster)	PFAS	0.64–0.66 ng/g ww	
		Organism tissues (lobster)	PFAS	0.22 ng/g ww	
Grass carp	MPs	Aquaculture water	Predominantly PP, PE	10.3–87.5 particulars/L	[74]
Multiple fish species	MPs	Lagoon water	PP, PE, HDPE, PS, etc.	0.00–0.30 particulars/L	[78]
		Organism tissues	PE, PP, nylon-12, polyacetylene	1–1.5 microplastics per fish	
Oyster	MPs	Seawater	PU, PA	144.27 ± 42.48 particulars/L	[75]
Eel and crayfish	MPs	Rice-fish culture station water	PE, PP, PVC	0.4 ± 0.1 particulars/L	[77]
		Organism tissues (fish)	PE, PP, PVC	3.3 ± 0.5 particulars/L	
		Organism tissues (shrimp)	PE, PP, PVC	2.5 ± 0.6 particulars/L	
Fish, crayfish, crab	MPs	Fish pond	PE, PP, PET, PVC	83–550 particulars/m^3	[76]
		Shrimp pond	PE, PP, PET, PA	233–733 particulars/m^3	
		Crab pond	PE, PP, PET, PS, PA	500–750 particulars/m^3	

TMP: Trimethoprim; CFX: Ciprofloxacin; SDZ: Sulfadiazine; SDM: Sulfadimethoxine; SQX: Sulfaquinoxaline; TC: Tetracycline; ETM: Erythromycin; CTM: Clarithromycin; RTM: Roxithromycin; AMX: Amoxicillin; FLO: Florfenicol; OXO: Oxolinic Acid; OTC: Oxytetracycline; SMX: Sulfamethoxazole; LIN: Lincomycin; ENR: Enrofloxacin; CIP: Ciprofloxacin; TPL: Thiamphenicol; PP: Polypropylene; PE: Polyethylene; HDPE: High-Density Polyethylene; PS: Polystyrene; PU: Polyurethane; PA: Polyamide; PVC: Polyvinyl Chloride; PET: Polyethylene Terephthalate; EDCs: Endocrine-Disrupting Compounds; PFAS: Per- and Polyfluoroalkyl Substances; MPs: Microplastics.

In terms of transformation and activation, certain pollutants can be converted into more toxic forms during environmental transport or metabolic processes[85], as exemplified by the transformation of PFAS precursors into terminal persistent pollutants such as perfluorooctane sulfonate (PFOS). Although antibiotics are susceptible to degradation, their continuous input results in persistent existence; ARGs can achieve long-distance dissemination via vectors such as microplastics[86]. Antibiotic residues function as a persistent selection pressure that further enriches ARB[66], increases the abundance of mobile genetic elements (MGEs)[87], and activates the HGT of ARGs[88], which promotes the transmission of resistance traits to human pathogens, amplifying the risk of clinical antimicrobial resistance. Even after complete degradation of antibiotics, ARGs can persist via mobile genetic elements, leading to an increase in ARGs without antibiotics[87]. Moreover, non-antibiotic factors, including heavy metals and microplastics, can improve ARGs transfer efficiency by several-fold via mechanisms such as oxidative stress induction, triggering 'non-antibiotic-driven resistance expansion'. For example, MNPs may serve as carriers facilitating the transfer of ARB and ARGs[88], while heavy metals can promote co-resistance to antibiotics in microorganisms, as the genes for these resistance phenotypes reside on the same genetic element[89].

Bioaccumulation and ecological risk transfer

In addition to multi-media migration, NCs are prone to bioaccumulation, resulting in the transmission of ecological risks. NCs constitute a critical pathway for human exposure through food chain transfer. Hydrophobic pollutants (such as alkylphenols, organochlorine pesticides, and certain PFAS) are prone to accumulating in adipose tissues due to their high lipophilicity[31], and undergo biomagnification along trophic levels, resulting in significantly elevated concentrations in high-trophic-level organisms[90,91]. For instance, the transformation of PFAS precursors in farmed salmon contributes to seafood contamination, ultimately posing dietary exposure risks. These exposure processes can be quantitatively assessed using models such as the estimated daily intake (EDI), risk quotient (RQ)[92], and the seafood risk tool (SRT)[93]. Moreover, EDCs such as steroid hormones can impair population sex

ratios and reproductive functions even at trace concentrations[94], with mixture exposures further amplifying ecological risks.

Unlike traditional hydrophobic pollutants, ARGs show a distinct horizontal enrichment of resistance patterns. Livestock chronically exposed to low-dose antibiotic environments impose selective pressure on their gut microbiota[70], leading to the enrichment of resistant bacteria carrying ARGs as dominant populations[95,96]. This resistance phenotype enrichment is synergistically promoted by the vector effect of MNPs[13], which is further promoted by bacterial-phage symbiosis[97]. Subsequently, through pathways such as manure application to farmland[98] and wastewater discharge[99], ARGs disseminate into the broader environment. This process not only facilitates the transmission of ecological risks[90,91] but also enables the transfer of resistance traits to humans via the food chain, effectively amplifying the spread and impact of antimicrobial resistance.

Interfacial and molecular mechanisms combined with the pollution of NCs

The combined pollution of NCs in livestock manure relies on interfacial processes centered on MNPs as core carriers. MNPs can bind heavy metals, EDCs, and ARGs through multiple interfacial forces including oxygen-containing functional group interactions, electrostatic interactions, and halogen bonds (Fig. 3). These interactions promote the aggregation of pollutants on the surface of MNPs, leading to the formation of stable composite particles[13].

MNPs in the moist matrix of livestock manure, which resembles freshwater environments, enter cells via phagocytosis. MNPs in saline microenvironments rely on macropinocytosis. Hydrophobic pollutants cross cell membranes through diffusion, while hydrophilic pollutants are transported via carrier proteins[100].

On the surface of MNPs, horizontal gene transfer of ARGs mediated by plasmids and vertical gene transfer in microorganisms can also amplify pollution risks. For example, large-sized PE microplastics, characterized by a rough surface and gaps, can provide stable habitats for microorganisms to promote biofilm formation, increasing the conjugative transfer efficiency of *tetW* and
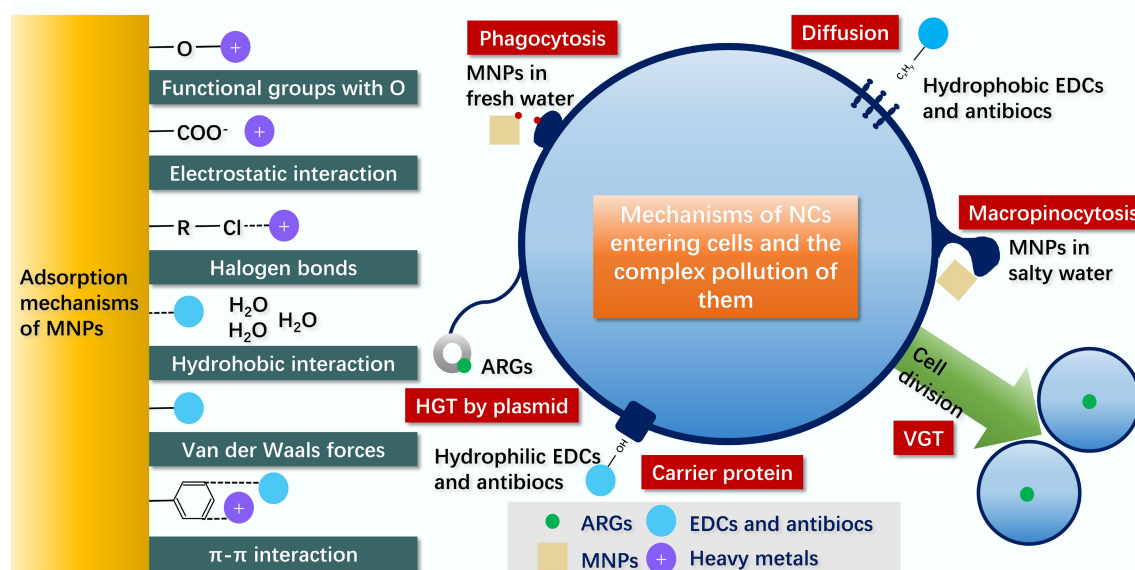

Fig. 3 Mechanisms of NCs entering cells and the complex pollution of them[13,66,81,88,100].

other ARGs by up to 1.7-fold[101]. These processes synergistically drive the persistence and spread of combined pollution in livestock manure.

Source reduction and synergistic control technologies

Source reduction and functional alternatives

Within aquaculture systems, antibiotics can be reduced at the source through the adoption of substitutes or alternative strategies. Compounds such as essential oils[102], chicken immunoglobulins[103], antimicrobial peptides[104], and organic acids[105] serve as effective antibiotic alternatives. Dietary microspheres have been shown to enhance antibiotic utilization efficiency[106], while autogenous vaccines can improve organism immunity to reduce antibiotic dependence[107]. Additionally, probiotics, prebiotics, and fibrous feed components contribute to the modulation of gut microbiota[108]. To optimize the delivery of these bioactive substances, encapsulation systems can be employed to improve drug transport efficacy[109].

By strengthening regulatory oversight and emission control of antibiotic use in livestock farming, the implementation of precision medication techniques (such as on-demand administration) can reduce antibiotic application by 30%–50%. In livestock and poultry farming, probiotics (such as *Bacillus* spp.) and plant extracts (such as allicin) serve as antibiotic alternatives for growth promotion, lowering the input of antibiotic residues[110]. In swine feed, the supplementation of lysozyme and enzymatic preparations (such as amylase, protease, non-starch polysaccharidases, and phytase) improves nutrient digestibility, reduces the accumulation of undigested substrates in the hindgut, and modifies the gut microbial fermentation environment, directly diminishing the abundance of ARB[111].

End-of-pipe treatment and advanced removal technologies

In the field of antibiotic treatment in aquaculture wastewater, advanced oxidation processes based on persulfate have attracted significant research interest due to the advantages offered by sulfate radicals ($\cdot SO_4^-$), including a broad pH adaptability and a relatively long half-life[112]. The efficacy of this technology can be further improved through electrochemical activation[113], coupling with ferrate, or the addition of catalysts[114,115]. In comparison, ozonation, while effective in antibiotic removal[116], is more suitable for freshwater aquaculture systems as it readily reacts with anions such as halogens in seawater to generate harmful disinfection by-products.

In the realm of biological treatment, the membrane aerated biofilm reactor enables effective optimization of functional microbial community structure through precise regulation of aeration pressure, enhancing system stability and removal efficiency[117]. Building on this, the implementation of bioaugmentation strategies (such as the introduction of synthetic microbial consortia) not only improves antibiotic degradation capacity but also significantly mitigates the dissemination risk of ARGs.

Adsorption and flocculation treatment

Adsorption technology utilizes interfacial interactions (such as van der Waals forces and electrostatic attraction) on porous materials to efficiently remove NCs from water, offering advantages such as low cost and operational simplicity. For instance, a bio-inspired graphene oxide sponge shows an adsorption capacity of up to 1,006 mg/g for diclofenac[118]. Biofloc technology operates in a zero-water-exchange mode, suppressing pathogens through microbial competition and converting the resulting flocs into supplementary feed, achieving dual benefits of pollution control and feed substitution. Biochar from agricultural biomass demonstrates an adsorption rate of up to 99% for ternary antibiotic mixtures[119], and at a pH of 7.56, it achieves a removal efficiency of > 95% for microplastic spheres at a concentration of $1.08 \pm 0.2 \times 10^8$ particles/L[120].

Advanced oxidation technology

Utilizing strong oxidants such as hydroxyl radicals ($\cdot OH$), hydroperoxyl radicals ($\cdot HO_2^-$), superoxide radicals ($\cdot O_2^-$), sulphate radicals ($\cdot SO_4^-$), chlorine radicals ($\cdot Cl$), ozone (O_3), and organic peroxy radicals ($\cdot ROO$) to oxidize and degrade pollutants in wastewater[121]. Their activation is typically achieved through Fenton/Fenton-like oxidation, ozonation, UV irradiation, electrocatalytic oxidation, photocatalysis, wet oxidation, or combinations of these processes[122]. Ozone nanobubbles can remain suspended in water for hours or even months, enabling high gas transfer efficiency. They possess high oxidation potential, low buoyancy, and generate free radicals[123]. A hybrid nanobubble-forward osmosis (NB-FO) system has been employed for treating and reusing aquaculture wastewater[124].

Biological and ecological treatment

Biological and ecological remediation technologies have garnered widespread attention in the field of aquaculture wastewater treatment due to their high efficiency and low operational costs. Moving bed biofilm reactors and fixed bed biofilm reactors utilize carbon-based media such as wood chips and corn cobs as both biofilm carriers and denitrification carbon sources. Under optimized C/N ratios, these systems effectively facilitate pollutant degradation[125]. Notably, the dissimilatory nitrate reduction to ammonium (DNRA) process can account for up to 23% of the nitrogen transformation[126], highlighting its significance in regulating nitrogen conversion pathways[121]. Recirculating aquaculture systems (RAS) achieve closed-loop water recycling and pollution control by integrating physical filtration, biological purification, and disinfection units[127]. Membrane bioreactors innovatively combine membrane separation with biological degradation, demonstrating strong potential for efficient removal of organic matter and pathogenic microorganisms[128]. There are differences in the removal effects of biotechnological fermentation (anaerobic digestion) and composting on ARGs in livestock and poultry wastes. During the anaerobic digestion of swine manure, *tet* and *erm* genes show a 0.30 log decrease, while *sul*, *fca*, and *aac* genes increase by 1.4–52 times[129]. In some studies, *tet*, *erm*, and *sul* genes decrease by 1.03–4.23 log[130,131]. When treating cattle manure, the *fca* gene decreases by 1.77 times[132]. During the composting of swine manure, cattle manure, and poultry manure, various ARGs such as *tet*, *aac*, *mdr*, *sul*, and *bla* generally show a 0.70–1.9 log decrease[133]. ARGs in poultry manure also have a 0.92–1.4 log decrease[40]. Overall, most ARGs are significantly reduced, but some genes are enriched during anaerobic digestion (Table 4), so the process needs to be optimized according to specific scenarios. This phenomenon is driven by the synergy of multiple factors: Residual antibiotics and heavy metals from anaerobic digestion exert selective pressure through survival selection and co-resistance; specific dominant bacteria serve as primary hosts, whose proliferation and secretion of extracellular substances promote the enrichment of ARGs; mobile genetic elements such as transposons and integrons enhance the cross-species transmission of ARGs; the structural stability of genes such as *sul* and a relatively long sludge retention time (SRT, 12–52 d) provide a foundation for ARG accumulation[129,130,134].

Constructed wetlands, as a cost-effective ecological treatment technology, facilitate processes such as nitrification and denitrification through integrated plant-microbe-substrate systems. It has

Table 4 ARGs removal efficiency under different treatment strategies

Sample	Treatment	ARGs	Abundance after treatment	Removal efficiency	Ref.
Swine manure	Anaerobic digestion	*tet, erm*	1.0×10^{-1}–4×10^{-2} copies/16S rRNA	0.30 log decrease	[129]
		sul, fca, aac	9.07×10^{-1} copies/16S rRNA	1.4–52 times increase	[129]
		tet, sul, erm, fca	10^4–10^9 copies/g	1.45 times increase	[130]
		tet, erm, sul	$\sim 3 \times 10^{-2}$ copies/16S rRNA	1.03–4.23 log decrease	[131]
Cattle manure		*fca*	1.69×10^8 copies/g	1.77 times decrease	[132]
Swine manure	Composting	*tet, aac, mdr, sul, bla*	5×10^{-5} (percentage of iTags)	0.74–1.9 log decrease	[133]
Cattle manure		*tet, sul, aac, erm, bla, mdr, fca, van*	3×10^{-2} copies/16S rRNA	0.70 log decrease	[46]
		sul, erm aac, bla	4.6×10^6–5.01×10^9 copies/g	1.0–2.0 log decrease	[138]
Poultry manure		*aac, bla, fca, erm, mdr, sul, tet*, other *aac, bla, fca, erm, mdr, sul, tet*, other	8×10^{-2}–4×10^{-1} copies/16S rRNA	0.92–1.4 log decrease	[40]
Swine wastewater	Biological treatment process	*tet, sul, bla*	10–10^5 copies/mL	0.09–2.7 (*tet*), 0.17–1.7 (*sul*) 0.11–2.0 (*bla*) log decrease	[139]
		tet, sul, erm, fca, mcr	3.1×10–7.1×10^5 copies/mL	0.3–3.1 log decrease	[140]
		tet, sul	2.6×10^8–1.1×10 copies/mL	0.57–0.94 log decrease	[141]
		tet, sul	1.0×10^5–1.5×10^{10} copies/mL	0.1–3.3 log decrease	[142]
Swine wastewater	Constructed wetlands	*tet*	10^{-3}–10^{-1} copies/16S rRNA	0.26–3.0 log decrease	[143]
		tet	3×10^{-3}–1×10^{-2} copies/16S rRNA	0.18–2.0 log decrease	[144]
Aquaculture wastewater	Advanced oxidation technology	*sul1, tetX, intl1, qnrS*	–	1.02 (*sul1*), 1.09 (*tetX*), 0.33 (*intl1*) 0.33 (*qnrS*) log decrease	[114]

been indicated that their treatment efficiency is regulated by multiple factors: at the design level, substrate composition and flow type are critical[135]; at the operational level, hydraulic retention time and loading rate play decisive roles; and at the environmental level, factors such as temperature, pH, and salinity also significantly influence removal performance[136]. Particularly in coupled subsurface vertical and horizontal flow wetlands treating aquaculture wastewater, nitrification has been identified as the core mechanism governing treatment efficacy, achieving up to 98% removal of antibiotics[137]. A comparison of core governance technologies is shown in Table 5.

Integrated multiple-technology synergistic control systems

Current approaches relying on single technologies for controlling the environmental risks of NCs often face limitations[145]. Consequently, synergistic multi-technology systems have emerged as a central focus in both research and application. An integrated management framework spanning source reduction, process interception, and end treatment is increasingly adopted to address the synergistic effects of NCs. In the source reduction phase, the combination of advanced oxidation processes (such as UV/persulfate systems) and precision membrane separation (such as graphene-modified nanofiltration membranes) demonstrates strong potential. The former effectively degrades molecular structures of recalcitrant organics such as endocrine-disrupting chemicals, while the latter achieves molecular-level retention (> 99%) of compounds, including per- and polyfluoroalkyl substances. For microplastic removal, density separation (using NaCl or NaI solutions) and thermochemical treatment can be applied. Composting processes achieve microplastic removal rates of 13%–29%, while high-temperature pyrolysis (> 500 °C) enables complete degradation of microplastics[146].

At the levels of process interception and end treatment, the Integrated Multi-Technology systems (such as microbial fuel cells) with catalytic oxidation processes like electro-fenton enable simultaneous degradation of organic pollutants, *in situ* generation of electrical energy, and production of highly reactive radicals, leading to efficient antibiotic removal. For targeting specific contaminants, smart materials such as molecularly imprinted polymers offer a novel

pathway for highly selective adsorption. At the terminal treatment stage, coupled systems combining constructed wetlands with photocatalysis, along with advanced disinfection methods such as UV/chlorine, not only achieve deep mineralization of residual pollutants but also effectively disrupt antibiotic resistance genes, with efficiency reported to be two to three times higher than that of conventional methods[147,148]. Thermophilic composting combined with UV disinfection has achieved a 96.8% removal rate of antibiotic resistance genes in chicken manure, along with complete inactivation of heat-resistant pathogens[40]. Soil amendment with modified biochar (for source retention) coupled with permeable reactive barriers in groundwater (for end interception) has been shown to reduce PFAS migration distance by 80%[57]. The integration of composting and membrane separation technologies enables simultaneous removal of microplastics (removal rate > 80%) and ARGs (removal > 5 log) from manure[55]. Microbial fuel cell systems are often coupled with constructed wetlands for treating marine aquaculture wastewater containing heavy metals and antibiotics[149].

The synergistic removal of both new and conventional contaminants from aquaculture waste presents a promising strategy. It has been reported that a flocculation/ultrafiltration/nanofiltration system incorporating a layer-by-layer self-assembled nanofiltration membrane was developed, demonstrating effective removal of both conventional and new contaminants from actual aquaculture wastewater[150]. Furthermore, ecological engineering systems such as RAS[151] and constructed wetlands[152] integrate physical, chemical, and biological processes[153,154], enabling multi-pathway synergistic removal of contaminants. It has been indicated that constructed wetland systems achieve satisfactory removal efficiencies for most antibiotics and EDCs[155], and are applicable under various challenging conditions, including wastewater containing veterinary pharmaceuticals[156] and high-salinity mariculture effluents[157].

Furthermore, intelligent management platforms built on Internet of Things (IoT) and digital twin technologies enable closed-loop management. This includes real-time monitoring, and trend prediction, and dynamic optimization of process parameters. These platforms ensure the stable and efficient operation of multi-technology integrated systems and improve the overall effectiveness of the treatment framework.

Table 5 Core governance technologies comparison

Technology category	Specific technology	Target pollutants	Removal efficiency	Cost level	Technical complexity	Secondary pollution risk	Application scenarios	Core advantages	Limitations	Ref.
Source reduction technologies	Antibiotic substitutes (such as essential oils/antimicrobial peptides)	Pathogens, antibiotic-dependent needs	Antibiotic usage reduced by 30%–50%	Medium	Low	No	Feed additives, disease prevention	Reduces antibiotic input at the source, aligns with green aquaculture	High cost of some substitutes; efficacy varies by aquaculture species	[98] [102] [108]
	Precision medication + regulatory control	Excessive antibiotics, antibiotic residues	Antibiotic usage reduced by 30%–50%	Low	Medium	No	Large-scale livestock farms	Simple operation, easy to implement	Relies on farmers' cooperation; high regulatory costs	[108]
	Enzyme preparations/probiotic addition	ARB, harmful intestinal microorganisms	Significantly reduces ARB abundance	Medium	Low	No	Feed additive in livestock farming	Improves intestinal environment; synergistically enhances aquaculture benefits	Probiotic survival affected by feed processing technologies	[106] [109]
Advanced oxidation processes (AOPs)	Persulfate-based advanced oxidation	Refractory antibiotics, ARGs	Enrofloxacin (ENR) removal: 98%; ARGs reduced by 1.02–1.09 log units	Medium-High	Medium-High	Potential formation of small amounts of oxidation byproducts	End-of-pipe treatment of aquaculture wastewater	Wide pH adaptability; long half-life	Requires catalyst addition or energy input; high cost	[110] [111]
	Ozonation	Antibiotics, pathogens	Highly efficient antibiotic removal	Medium-High	Medium	Formation of harmful disinfection byproducts in seawater	End-of-pipe treatment of freshwater aquaculture wastewater	High oxidation efficiency; fast reaction rate	Not suitable for mariculture; byproduct risks	[114]
Adsorption and Flocculation technologies	Biochar adsorption	Antibiotics, microplastics, ARG carriers	Antibiotic adsorption rate: 99%; microplastic removal rate: > 95%	Low-Medium	Low	Incineration required after adsorption saturation	Pretreatment/advanced end-of-pipe treatment of various aquaculture wastewaters	Wide raw material sources; resource recycling potential	Regeneration or safe disposal required after saturation	[116] [118]
	Biofloc technology (BFT)	ARB, nitrogen and phosphorus pollutants	ARB inhibition rate: > 80%; Total Nitrogen (TN) removal: 60%–70%	Low	Medium	Dissolved oxygen (DO) < 2 mg/L due to excessive flocs	Zero-exchange aquaculture systems	Zero water exchange; dual functions of pollution control and feed substitution	Precise regulation of water quality parameters (such as C/N ratio) required	[117]
Biological and Ecological technologies	Anaerobic digestion	Organic pollutants, partial ARGs	tet/erm genes reduced by 0.30 log units; partial ARGs reduced by 1.03–4.23 log units	Low-Medium	Medium	ARG residues in biogas slurry	Treatment of aquaculture solid wastes	Biogas resource recovery; low energy consumption	Enrichment of partial ARGs (sul/fca/aac) likely	[131]
	Constructed wetland	Antibiotics, nitrogen and phosphorus, ARGs	Antibiotic removal rate: up to 98%	Low	Low	No	End-of-pipe treatment of small-to-medium scale aquaculture wastewater	Low cost; eco-friendly; synergistic landscape benefits	Large land occupation; affected by environmental factors	[135] [137]
	Recirculating aquaculture system (RAS)	Pollutants, pathogens, antibiotic residues	Closed-loop water reuse; efficient pollution control	High	High	No	High-end aquaculture	Water-saving and emission reduction; controllable aquaculture environment	High investment and operation costs; high technical requirements for maintenance	[125] [127]

Future prospects and challenges

This study aims to address the challenges posed by NCs in aquaculture systems. There is limited understanding of the combined toxic effects and cross-media migration of multiple pollutants under low-dose co-exposure conditions. Moreover, scalable and economically viable integrated processes for the simultaneous removal of diverse pollutants are still lacking. Future research should focus on (1) elucidating the interfacial behavior and synergistic effects of NCs to reveal their migration patterns and combined toxicity mechanisms under mixed exposure scenarios, (2) developing translational strategies from lab to application, including integrated treatment systems capable of removing both conventional and new contaminants, and (3) establishing an intelligent management framework that encompasses source reduction, process intervention, and end-of-pipe treatment, supported by real-time monitoring and interdisciplinary collaboration to enable science-based risk assessment.

Conclusions

Antibiotics (AR-ARB-ARGs), EDCs, and MNPs are widely detected in livestock and aquaculture wastes, exhibiting distinct compositional profiles dependent on farming practices. Notably, ARGs abundances in swine and poultry manure significantly exceed those in cattle and sheep manure. Meanwhile, aquaculture systems are characterized by a complex pollution spectrum dominated by antibiotics and EDCs. These new contaminants undergo multi-media migration and transformation in the environment. Compounds such as BPA exhibit 'persistent existence' due to continuous input, whereas polyhalogenated compounds display long-range transport potential owing to their chemical stability. MNPs act as carriers, exacerbating contaminant risks through the 'Trojan horse' effect. Importantly, even after antibiotic degradation, ARGs persist via horizontal gene transfer, resulting in an increase in ARGs without antibiotics in environmental reservoirs. Hydrophobic contaminants accumulate along the food chain, leading to elevated concentrations in high-trophic-level organisms. At the same time, ARGs spread through 'resistance level enrichment' in microbial communities, ultimately posing a risk to human health via dietary exposure. Given the limitations of standalone treatment technologies, an integrated 'source substitution-process interception-end treatment' strategy is urgently required. This comprehensive approach is essential not only for effective control of new contaminants in the aquaculture industry but also for facilitating sustainable sector transformation and advancing the global 'One Health' objective. To achieve synergistic contaminant removal and risk mitigation, future efforts should prioritize developing targeted replacement products, enhanced process interception mechanisms, and efficient end-treatment technologies.

Author contributions

The authors confirm their contributions to the paper as follows: Shuyu Sun: investigation, writing – original draft, visualization; Jingrui Deng: investigation, writing – original draft, visualization; Jingyi Li: writing – review & editing; Guixue Song: writing – review & editing; Siyuan Ye: writing – review & editing; Qigui Niu: conceptualization, writing – review & editing, supervision. All authors reviewed the results and approved the final version of the manuscript.

Data availability

All data generated or analyzed during this study are included in this published article.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

[1]School of Environmental Science and Engineering, China-America CRC for Environment & Health of Shandong Province, Shandong University, Qingdao, Shandong 266237, China; [2]Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, Shandong University, Qingdao, Shandong 266237, China; [3]Qingdao Key Laboratory of Marine Pollutant Prevention, Shandong University, Qingdao, Shandong 266237, China; [4]Institute of Marine Science and Technology, Shandong University, Qingdao, Shandong 266237, China; [5]Key Laboratory of Coastal Wetland Biogeosciences, Qingdao Institute of Marine Geology, China Geological Survey, Qingdao, Shandong 266237, China

References

[1] Wu D, Cui D, Zhou M, Ying Y. 2022. Information perception in modern poultry farming: a review. *Computers and Electronics in Agriculture* 199:107131

[2] FAO. 2017. *The future of food and agriculture – trends and challenges*. FAO, Rome

[3] DeWeerdt S. 2020. Can aquaculture overcome its sustainability challenges? *Nature* 588:S60−S62

[4] Tao Y, Wang J, Chen Y, Tan C, Guo H. 2025. Development of traceability systems: a methodological overview toward effective regulation of emerging contaminants. *Journal of Hazardous Materials* 495:139058

[5] Zhu Z, Li L, Yu Y, Tan L, Wang Z, et al. 2023. Distribution, source, risk and phytoremediation of polycyclic aromatic hydrocarbons (PAHs) in typical urban landscape waters recharged by reclaimed water. *Journal of Environmental Management* 330:117214

[6] Mougin J, Labreuche Y, Boulo V, Goudenège D, Saad J, et al. 2025. Antibiotic use in oyster hatcheries promotes rapid spread of a highly transferable and modular resistance plasmid in *Vibrio*. *The ISME Journal* 19:wraf163

[7] Kozlova TA, Hardy BP, Levin DB. 2020. Effect of fish steroids 17β-estradiol and $17,20\beta$-dihydroxy-4-pregnen-3-one on growth, accumulation of pigments, and fatty acid profiles in the microalgae *Scenedesmus quadricauda* (CPCC-158). *Renewable Energy* 148:798−806

[8] Lin L, Huang Y, Wang P, Chen CC, Qian W, et al. 2023. Environmental occurrence and ecotoxicity of aquaculture-derived plastic leachates. *Journal of Hazardous Materials* 458:132015

[9] Ali AM, Berntssen MHG, Sele V, Valdersnes S. 2025. Wide scope screening and target quantification of per- and polyfluoroalkyl substances (PFAS) in feed and feed ingredients to farmed salmonids. *Journal of Hazardous Materials* 495:139078

[10] Tahir R, He K, Yan H, Shrestha A, Li XH, et al. 2025. Chronic abamectin induces hepatotoxicity and endoplasmic reticulum stress in large-mouth bass (*Micropterus salmoides*): potential mitigation by curcumin and human health risk assessment. *Journal of Hazardous Materials* 495:133876

[11] Xiong X, Xie S, Feng K, Wang Q. 2022. Occurrence of microplastics in a pond-river-lake connection water system: how does the aquaculture process affect microplastics in natural water bodies. *Journal of Cleaner Production* 352:131632

[12] Shah BA, Malhotra H, Papade SE, Dhamale T, Ingale OP, et al. 2024. Microbial degradation of contaminants of emerging concern: metabolic, genetic and omics insights for enhanced bioremediation. *Frontiers in Bioengineering and Biotechnology* 12:1470522

[13] Xie S, Hamid N, Zhang T, Zhang Z, Peng L. 2024. Unraveling the nexus: microplastics, antibiotics, and ARGs interactions, threats and control in aquaculture - a review. *Journal of Hazardous Materials* 471:134324

[14] Annamalai J, Namasivayam V. 2015. Endocrine disrupting chemicals in the atmosphere: their effects on humans and wildlife. *Environment International* 76:78−97

[15] Medvedev AV, Medvedeva LA, Martsen E, Moeser M, Gorman KL, et al. 2020. Harmonized cross-species assessment of endocrine and metabolic disruptors by ecotox FACTORIAL assay. *Environmental Science & Technology* 54:12142−12153

[16] Segner H, Caroll K, Fenske M, Janssen CR, Maack G, et al. 2003. Identification of endocrine-disrupting effects in aquatic vertebrates and invertebrates: report from the European IDEA project. *Ecotoxicology and Environmental Safety* 54:302−314

[17] Aris AZ, Shamsuddin AS, Praveena SM. 2014. Occurrence of 17α-ethynylestradiol (EE2) in the environment and effect on exposed biota: a review. *Environment International* 69:104−119

[18] Solecki R, Kortenkamp A, Bergman Å, Chahoud I, Degen GH, et al. 2017. Scientific principles for the identification of endocrine-disrupting chemicals: a consensus statement. *Archives of Toxicology* 91:1001−1006

[19] Koenig S, Porte C, Solé M, Sturve J. 2013. Biliary PAH and alkylphenol metabolites, biomarker enzyme activities, and gene expression levels in the deep-sea fish *Alepocephalus rostratus*. *Environmental Science & Technology* 47:2854−2861

[20] Fernandes D, Zanuy S, Bebianno MJ, Porte C. 2008. Chemical and biochemical tools to assess pollution exposure in cultured fish. *Environmental Pollution* 152:138−146

[21] Zhong S, Li R, Tian Y, Wei Z, Zhang L, et al. 2024. Integrative models for environmental forecasting of phthalate migration from microplastics in aquaculture environments. *Journal of Hazardous Materials* 480:136194

[22] Guillette TC, McCord J, Guillette M, Polera ME, Rachels KT, et al. 2020. Elevated levels of per- and polyfluoroalkyl substances in Cape Fear River Striped Bass (*Morone saxatilis*) are associated with biomarkers of altered immune and liver function. *Environment International* 136:105358

[23] Sznajder-Katarzyńska K, Surma M, Cieślik I. 2019. A review of perfluoroalkyl acids (PFAAs) in terms of sources, applications, human exposure, dietary intake, toxicity, legal regulation, and methods of determination. *Journal of Chemistry* 2019:2717528

[24] Hannisdal R, Nøstbakken OJ, Berntssen MHG, Duinker A, Ho QT, et al. 2025. Nutrients and contaminants in farmed Atlantic salmon (*Salmo salar*) fillet and fish feed from 2006 to 2021. *Journal of Agriculture and Food Research* 21:101933

[25] Li C, Li Y, Li X, Ma X, Ru S, et al. 2021. Veterinary antibiotics and estrogen hormones in manures from concentrated animal feedlots and their potential ecological risks. *Environmental Research* 198:110463

[26] Xu P, Zhou X, Xu D, Xiang Y, Ling W, et al. 2018. Contamination and risk assessment of estrogens in livestock manure: a case study in Jiangsu Province, China. *International Journal of Environmental Research and Public Health* 15:125

[27] Gu Y, Yu J, Hu X, Yin D. 2016. characteristics of the alkylphenol and bisphenol a distributions in marine organisms and implications for human health: a case study of the East China Sea. *Science of The Total Environment* 539:460−469

[28] Acosta A, Tirkaso W, Nicolli F, Van Boeckel TP, Cinardi G, et al. 2025. The future of antibiotic use in livestock. *Nature Communications* 16:2469

[29] Shi Y, Liang M, Zeng J, Wang Z, Zhang L, et al. 2024. Soil amoebae are unexpected hotspots of environmental antibiotics and antibiotic resistance genes. *Environmental Science & Technology* 58:21475−21488

[30] Li B, Qiu Y, Song Y, Lin H, Yin H. 2019. Dissecting horizontal and vertical gene transfer of antibiotic resistance plasmid in bacterial community using microfluidics. *Environment International* 131:105007

[31] Rysz M, Alvarez PJJ. 2004. Amplification and attenuation of tetracycline resistance in soil bacteria: aquifer column experiments. *Water Research* 38:3705−3712

[32] Su HC, Pan CG, Ying GG, Zhao JL, Zhou LJ, et al. 2014. Contamination profiles of antibiotic resistance genes in the sediments at a catchment scale. *Science of The Total Environment* 490:708−714

[33] Li S, Zhang C, Li F, Hua T, Zhou Q, et al. 2021. Technologies towards antibiotic resistance genes (ARGs) removal from aquatic environment: a critical review. *Journal of Hazardous Materials* 411:125148

[34] Munk P, Knudsen BE, Lukjancenko O, Duarte ASR, Van Gompel L, et al. 2018. Abundance and diversity of the faecal resistome in slaughter pigs and broilers in nine European countries. *Nature Microbiology* 3:898−908

[35] Dawson AL, Bose U, Escobar-Correas S, Yap K, Craik DJ, et al. 2025. Where have you been? Backtracking microplastic to its source using the biomolecular composition of the ecocorona. *Environmental Science & Technology* 59:22227−22238

[36] Koelmans AA, Redondo-Hasselerharm PE, Nor NHM, de Ruijter VN, Mintenig SM, et al. 2022. Risk assessment of microplastic particles. *Nature Reviews Materials* 7:138−152

[37] Hu L, Zhao Y, Xu H. 2022. Trojan horse in the intestine: a review on the biotoxicity of microplastics combined environmental contaminants. *Journal of Hazardous Materials* 439:129652

[38] Geyer R, Jambeck JR, Law KL. 2017. Production, use, and fate of all plastics ever made. *Science Advances* 3:e1700782

[39] Murata M, Kang JH. 2018. Bisphenol A (BPA) and cell signaling pathways. *Biotechnology Advances* 36:311−327

[40] Qian X, Gu J, Sun W, Wang XJ, Su JQ, et al. 2018. Diversity, abundance, and persistence of antibiotic resistance genes in various types of animal manure following industrial composting. *Journal of Hazardous Materials* 344:716−722

[41] Qiu T, Huo L, Guo Y, Gao M, Wang G, et al. 2022. Metagenomic assembly reveals hosts and mobility of common antibiotic resistome in animal manure and commercial compost. *Environmental Microbiome* 17:42

[42] Peng S, Zhang H, Song D, Chen H, Lin X, et al. 2022. Distribution of antibiotic, heavy metals and antibiotic resistance genes in livestock and poultry feces from different scale of farms in Ningxia, China. *Journal of Hazardous Materials* 440:129719

[43] Rothrock MJ, Min BR, Castleberry L, Waldrip H, Parker D, et al. 2021. Antibiotic resistance, antimicrobial residues, and bacterial community diversity in pasture-raised poultry, swine, and beef cattle manures. *Journal of Animal Science* 99:skab144

[44] Van Boeckel TP, Brower C, Gilbert M, Grenfell BT, Levin SA, et al. 2015. Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences of the United States of America* 112:5649−5654

[45] He Y, Yuan Q, Mathieu J, Stadler L, Senehi N, et al. 2020. Antibiotic resistance genes from livestock waste: occurrence, dissemination, and treatment. *npj Clean Water* 3:4

[46] Gou M, Hu HW, Zhang YJ, Wang JT, Hayden H, et al. 2018. Aerobic composting reduces antibiotic resistance genes in cattle manure and the resistome dissemination in agricultural soils. *Science of The Total Environment* 612:1300−1310

[47] Peak N, Knapp CW, Yang RK, Hanfelt MM, Smith MS, et al. 2007. Abundance of six tetracycline resistance genes in wastewater lagoons at

cattle feedlots with different antibiotic use strategies. *Environmental Microbiology* 9:143–151

[48] García-Galán MJ, Garrido T, Fraile J, Ginebreda A, Díaz-Cruz MS, et al. 2011. Application of fully automated online solid phase extraction-liquid chromatography-electrospray-tandem mass spectrometry for the determination of sulfonamides and their acetylated metabolites in groundwater. *Analytical and Bioanalytical Chemistry* 399:795–806

[49] Zhu L, Lian Y, Lin D, Huang D, Yao Y, et al. 2022. Insights into microbial contamination in multi-type manure-amended soils: the profile of human bacterial pathogens, virulence factor genes and antibiotic resistance genes. *Journal of Hazardous Materials* 437:129356

[50] Wu RT, Cai YF, Chen YX, Yang YW, Xing SC, et al. 2021. Occurrence of microplastic in livestock and poultry manure in South China. *Environmental Pollution* 277:116790

[51] Munoz G, Michaud AM, Liu M, Vo Duy S, Montenach D, et al. 2022. Target and nontarget screening of PFAS in biosolids, composts, and other organic waste products for land application in France. *Environmental Science & Technology* 56:6056–6068

[52] Zhu YG, Johnson TA, Su JQ, Qiao M, Guo GX, et al. 2013. Diverse and abundant antibiotic resistance genes in Chinese swine farms. *Proceedings of the National Academy of Sciences of the United States of America* 110:3435–3440

[53] Tao HY, Zhang J, Shi J, Guo W, Liu X, et al. 2021. Occurrence and emission of phthalates, bisphenol A, and oestrogenic compounds in concentrated animal feeding operations in Southern China. *Ecotoxicology and Environmental Safety* 207:111521

[54] Sarmah AK, Northcott GL, Leusch FDL, Tremblay LA. 2006. A survey of endocrine disrupting chemicals (EDCs) in municipal sewage and animal waste effluents in the Waikato region of New Zealand. *Science of The Total Environment* 355:135–144

[55] Sheriff I, Yusoff MS, Manan TSBA, Koroma M. 2023. Microplastics in manure: Sources, analytical methods, toxicodynamic, and toxicokinetic endpoints in livestock and poultry. *Environmental Advances* 12:100372

[56] Li H, Yang Z, Jiang F, Li L, Li Y, et al. 2023. Detection of microplastics in domestic and fetal pigs' lung tissue in natural environment: a preliminary study. *Environmental Research* 216:114623

[57] de Souza BB, Meegoda J. 2024. Insights into PFAS environmental fate through computational chemistry: a review. *Science of The Total Environment* 926:171738

[58] Ramachandraiah K, Ameer K, Jiang G, Hong GP. 2022. Micro- and nanoplastic contamination in livestock production: entry pathways, potential effects and analytical challenges. *Science of The Total Environment* 844:157234

[59] Beni NN, Karimifard S, Gilley J, Messer T, Schmidt A, et al. 2023. Higher concentrations of microplastics in runoff from biosolid-amended croplands than manure-amended croplands. *Communications Earth & Environment* 4:42

[60] Chai J, Zhuang Y, Cui K, Bi Y, Zhang N. 2024. Metagenomics reveals the temporal dynamics of the rumen resistome and microbiome in goat kids. *Microbiome* 12:14

[61] Han XM, Hu HW, Chen QL, Yang LY, Li HL, et al. 2018. Antibiotic resistance genes and associated bacterial communities in agricultural soils amended with different sources of animal manures. *Soil Biology & Biochemistry* 126:91–102

[62] Ogunfowora LA, Iwuozor KO, Ighalo JO, Igwegbe CA. 2021. Trends in the treatment of aquaculture effluents using nanotechnology. *Cleaner Materials* 2:100024

[63] Healey N. 2020. Aquaculture's role in propagating antimicrobial resistance must be addressed. *Nature* 586:S63

[64] Hites RA, Foran JA, Carpenter DO, Hamilton MC, Knuth BA, et al. 2004. Global assessment of organic contaminants in farmed salmon. *Science* 303:226–229

[65] Wang C, Liu X, Yang Y, Wang Z. 2021. Antibiotic and antibiotic resistance genes in freshwater aquaculture ponds in China: a meta-analysis and assessment. *Journal of Cleaner Production* 329:129719

[66] Dong H, Chen Y, Wang J, Zhang Y, Zhang P, et al. 2021. Interactions of microplastics and antibiotic resistance genes and their effects on the aquaculture environments. *Journal of Hazardous Materials* 403:123961

[67] Choi S, Sim W, Jang D, Yoon Y, Ryu J, et al. 2020. Antibiotics in coastal aquaculture waters: occurrence and elimination efficiency in oxidative water treatment processes. *Journal of Hazardous Materials* 396:122585

[68] Su H, Duan S, Hu X, Xu W, Xu Y, et al. 2024. Spatiotemporal dynamics, bioaccumulation, and critical influencing factors of antibiotics in tilapia aquaculture: a study on source identification and environmental fate within typical farming systems. *Journal of Hazardous Materials* 477:135328

[69] Chen H, Liu S, Xu XR, Diao ZH, Sun KF, et al. 2018. Tissue distribution, bioaccumulation characteristics and health risk of antibiotics in cultured fish from a typical aquaculture area. *Journal of Hazardous Materials* 343:140–148

[70] Xu F, Yang C, Liu H, Liu H, Chen M, et al. 2025. Critical control points in *Penaeus vannamei* aquaculture: dynamic tracking and comprehensive risk assessment of antibiotics. *Journal of Hazardous Materials* 496:139256

[71] Abafe OA, Macheka LR, Abafe OT, Chokwe TB. 2021. Concentrations and human exposure assessment of per and polyfluoroalkyl substances in farmed marine shellfish in South Africa. *Chemosphere* 281:130985

[72] Zafeiraki E, Gebbink WA, Hoogenboom RLAP, Kotterman M, Kwadijk C, et al. 2019. Occurrence of perfluoroalkyl substances (PFASs) in a large number of wild and farmed aquatic animals collected in the Netherlands. *Chemosphere* 232:415–423

[73] Kolodziej EP, Harter T, Sedlak DL. 2004. Dairy wastewater, aquaculture, and spawning fish as sources of steroid hormones in the aquatic environment. *Environmental Science & Technology* 38:6377–6384

[74] Ma J, Niu X, Zhang D, Lu L, Ye X, et al. 2020. High levels of microplastic pollution in aquaculture water of fish ponds in the Pearl River Estuary of Guangzhou, China. *Science of The Total Environment* 744:140679

[75] Li J, Liu J, Wang X, Zhang T, Wang D, et al. 2024. Vertical transfer of microplastics in nearshore water by cultured filter-feeding oysters. *Journal of Hazardous Materials* 475:134769

[76] Xiong X, Liu Q, Chen X, Wang R, Duan M, et al. 2021. Occurrence of microplastic in the water of different types of aquaculture ponds in an important lakeside freshwater aquaculture area of China. *Chemosphere* 282:131126

[77] Lv W, Zhou W, Lu S, Huang W, Yuan Q, et al. 2019. Microplastic pollution in rice-fish co-culture system: a report of three farmland stations in Shanghai, China. *Science of The Total Environment* 652:1209–1218

[78] Garcés-Ordóñez O, Saldarriaga-Vélez JF, Espinosa-Díaz LF, Patiño AD, Cusba J, et al. 2022. Microplastic pollution in water, sediments and commercial fish species from Ciénaga Grande de Santa Marta lagoon complex, Colombian Caribbean. *Science of The Total Environment* 829:154643

[79] Yu X, Gutang Q, Wang Y, Wang S, Li Y, et al. 2024. Microplastic and associated emerging contaminants in marine fish from the South China Sea: exposure and human risks. *Journal of Hazardous Materials* 480:136200

[80] Wang F, Xiang L, Leung KSY, Elsner M, Zhang Y, et al. 2024. Emerging contaminants: a One Health perspective. *The Innovation* 5:100612

[81] Okamoto N, Viswanatha R, Bittar R, Li Z, Haga-Yamanaka S, et al. 2018. A membrane transporter is required for steroid hormone uptake in *Drosophila*. *Developmental Cell* 47:294–305.e7

[82] Wang Y, Wang F, Xiang L, Liao M, Wang M, et al. 2025. Co-exposure of di(2-ethylhexyl) phthalate (DEHP) decreased the submicron plastic stress in soil–plant system. *Eco-Environment & Health* 4:100184

[83] Mahoney H, Xie Y, Brinkmann M, Giesy JP. 2022. Next generation per- and poly-fluoroalkyl substances: status and trends, aquatic toxicity, and risk assessment. *Eco-Environment & Health* 1:117–131

[84] Liu J, Xu G, Zhao S, He J. 2024. Plastisphere microbiomes respiring persistent organohalide pollutants. *Environmental Science & Technology* 58:14740–14752

[85] Jepson PD, Law RJ. 2016. Persistent pollutants, persistent threats. *Science* 352:1388–1389

[86] Zhao Y, Zhang XX, Zhao Z, Duan C, Chen H, et al. 2018. Metagenomic analysis revealed the prevalence of antibiotic resistance genes in

the gut and living environment of freshwater shrimp. *Journal of Hazardous Materials* 350:10–18

[87] Chi W, Zou Y, Qiu T, Shi W, Tang L, et al. 2024. Horizontal gene transfer plays a crucial role in the development of antibiotic resistance in an antibiotic-free shrimp farming system. *Journal of Hazardous Materials* 476:135150

[88] Su H, Xu W, Hu X, Xu Y, Wen G, et al. 2025. The impact of microplastics on antibiotic resistance genes, metal resistance genes, and bacterial community in aquaculture environment. *Journal of Hazardous Materials* 489:137704

[89] Li Z, Junaid M, Chen G, Wang J. 2022. Interactions and associated resistance development mechanisms between microplastics, antibiotics and heavy metals in the aquaculture environment. *Reviews in Aquaculture* 14:1028–1045

[90] Khalifa HO, Shikoray L, Mohamed MI, Habib I, Matsumoto T. 2024. Veterinary drug residues in the food chain as an emerging public health threat: sources, analytical methods, health impacts, and preventive measures. *Foods* 13:1629

[91] Leichtweis J, Vieira Y, Welter N, Silvestri S, Dotto GL, et al. 2022. A review of the occurrence, disposal, determination, toxicity and remediation technologies of the tetracycline antibiotic. *Process Safety and Environmental Protection* 160:25–40

[92] Odinga ES, Zhou X, Mbao EO, Ali Q, Waigi MG, et al. 2022. Distribution, ecological fate, and risks of steroid estrogens in environmental matrices. *Chemosphere* 308:136370

[93] Stentiford GD, Peeler EJ, Tyler CR, Bickley LK, Holt CC, et al. 2022. A seafood risk tool for assessing and mitigating chemical and pathogen hazards in the aquaculture supply chain. *Nature Food* 3:169–178

[94] Ojoghoro JO, Scrimshaw MD, Sumpter JP. 2021. Steroid hormones in the aquatic environment. *Science of The Total Environment* 792:148306

[95] Tian L, Fang G, Li G, Li L, Zhang T, et al. 2024. Metagenomic approach revealed the mobility and co-occurrence of antibiotic resistomes between non-intensive aquaculture environment and human. *Microbiome* 12:107

[96] Jin X, Liu S, Zhang Z, Liu T, Li N, et al. 2023. Enrofloxacin-induced transfer of multiple-antibiotic resistance genes and emergence of novel resistant bacteria in red swamp crayfish guts and pond sediments. *Journal of Hazardous Materials* 443:130261

[97] Xia R, Yin X, Balcazar JL, Huang D, Liao J, et al. 2025. Bacterium-phage symbiosis facilitates the enrichment of bacterial pathogens and antibiotic-resistant bacteria in the plastisphere. *Environmental Science & Technology* 59:2948–2960

[98] Zhang YJ, Hu HW, Chen QL, Singh BK, Yan H, et al. 2019. Transfer of antibiotic resistance from manure-amended soils to vegetable microbiomes. *Environment International* 130:104912

[99] Yu T, Huang Y, Zhang Y, Wang S, Wang X, et al. 2025. Manure input propagated antibiotic resistance genes and virulence factors in soils by regulating microbial carbon metabolism. *Environmental Pollution* 375:126293

[100] Ramsperger AFRM, Wieland S, Wilde MV, Fröhlich T, Kress H, et al. 2025. Cellular internalization pathways of environmentally exposed microplastic particles: phagocytosis or macropinocytosis? *Journal of Hazardous Materials* 489:137647

[101] Yu X, Zhou ZC, Shuai XY, Lin ZJ, Liu Z, et al. 2023. Microplastics exacerbate co-occurrence and horizontal transfer of antibiotic resistance genes. *Journal of Hazardous Materials* 451:131130

[102] Srinivasan R, Jin X, Lin X, Zhao Z. 2025. Essential oil compounds as antibiotic alternatives: a comprehensive review of antibacterial, anti-quorum sensing, and antibiofilm effects against *Vibrio* spp. in Aquaculture. *Reviews in Aquaculture* 17:e70065

[103] Zhang L, Lin L, Qin Z. 2024. A review on the application of chicken immunoglobulin Y in aquaculture. *Reviews in Aquaculture* 16:536–551

[104] Lu J, Zhang Y, Wu J, Wang J. 2022. Intervention of antimicrobial peptide usage on antimicrobial resistance in aquaculture. *Journal of Hazardous Materials* 427:128154

[105] Ng WK, Koh CB. 2017. The utilization and mode of action of organic acids in the feeds of cultured aquatic animals. *Reviews in Aquaculture* 9:342–368

[106] Zhang M, Cai Z, Zhang G, Zhang Y, Xue N, et al. 2021. Effectively reducing antibiotic contamination and resistance in fishery by efficient gastrointestine-blood delivering dietary millispheres. *Journal of Hazardous Materials* 409:125012

[107] Barnes AC, Rudenko O, Landos M, Dong HT, Lusiastuti A, et al. 2022. Autogenous vaccination in aquaculture: a locally enabled solution towards reduction of the global antimicrobial resistance problem. *Reviews in Aquaculture* 14:907–918

[108] Haygood AM, Jha R. 2018. Strategies to modulate the intestinal microbiota of Tilapia (*Oreochromis* sp.) in aquaculture: a review. *Reviews in Aquaculture* 10:320–333

[109] Dezfooli SM, Gutierrez-Maddox N, Alfaro A, Seyfoddin A. 2019. Encapsulation for delivering bioactives in aquaculture. *Reviews in Aquaculture* 11:631–660

[110] Hasan MM, Fahim FJ, Rana S, Uddin S, Tonny MFS, et al. 2025. Antimicrobial potential and stability of *Lactobacillus acidophilus*-derived bacteriocins against multidrug-resistant common foodborne pathogens. *Applied Food Research* 5:100728

[111] Gao X, Ding J, Liao C, Xu J, Liu X, et al. 2021. Defensins: the natural peptide antibiotic. *Advanced Drug Delivery Reviews* 179:114008

[112] Patel A, Raikar LG, Gandhi J, Prakash H. 2025. Degradation of cefixime antibiotic by continuous flow ultraviolet-C persulfate based advanced oxidation process: fresh and marine water matrices, antibacterial activity removal, and cost analysis. *Chemical Engineering Journal* 512:162178

[113] Long L, Li J, Hou T, Liu M, Lin Y, et al. 2024. Removal of antibiotics from aquaculture wastewater using a continuous flow/EC/PMS coupled system. *Chemical Engineering Journal* 499:156278

[114] Li R, Wu X, Han Z, Xu L, Gan L, et al. 2023. Removal of antibiotic-resistant bacteria and genes by Solar-activated Ferrate/Peroxymonosulfate: efficiency in aquaculture wastewater and mechanism. *Chemical Engineering Journal* 474:145547

[115] Lu F, Chen Y, Huang J, Lin J, Zhang Y, et al. 2025. Peroxymonosulfate activation by peanut shell biochar-doped $BiFeO_3$ composite to remove antibiotic resistant bacteria from aquaculture wastewater. *Biochar* 7:104

[116] Kim T, Lee HYH, Kim CM, Jang A. 2023. Elucidating the relation between residual oxidants formation behavior and quinolone antibiotic removal efficiency on catalytic ozonation in seawater-based aquaculture wastewater. *Journal of Cleaner Production* 426:138779

[117] Chen X, Lei X, Zhu Y, Yan S, Li Y, et al. 2025. Enhanced removal of tetracycline and doxycycline in aquaculture pond sediments via synthetic bacterial consortium: efficacy and ecological risk assessment. *Journal of Hazardous Materials* 495:138997

[118] Rezvani H, Costantino J, Kapadia M, Majooni Y, Abioye SO, et al. 2025. Bio-inspired graphene oxide sponges for enhanced adsorption of legacy and emerging contaminants from water. *Journal of Water Process Engineering* 77:108329

[119] Schmidt MP, Ashworth DJ, Celis N, Ibekwe AM. 2023. Optimizing date palm leaf and pistachio shell biochar properties for antibiotic adsorption by varying pyrolysis temperature. *Bioresource Technology Reports* 21:101325

[120] Rajput P, Kumar P, Priya AK, Kumari S, Shiade SRG, et al. 2024. Nanomaterials and biochar mediated remediation of emerging contaminants. *Science of The Total Environment* 916:170064

[121] Liu X, Wang Y, Liu H, Zhang Y, Zhou Q, et al. 2024. A systematic review on aquaculture wastewater: pollutants, impacts, and treatment technology. *Environmental Research* 262:119793

[122] Zhang N, Chen J, Fang Z, Tsang EP. 2019. Ceria accelerated nanoscale zerovalent iron assisted heterogenous Fenton oxidation of tetracycline. *Chemical Engineering Journal* 369:588–599

[123] Shen Y, Chen Z, Shen J, Wang B, Yan P, et al. 2025. A pilot-scale study of *in situ* granular activated carbon regeneration via ozone micro-nano bubbles oxidation for long-lasting micropollutant purification in water. *Chemical Engineering Journal* 523:168434

[124] Farid MU, Choi PJ, Kharraz JA, Lao JY, St-Hilaire S, et al. 2022. Hybrid nanobubble-forward osmosis system for aquaculture wastewater treatment and reuse. *Chemical Engineering Journal* 435:135164

[125] Ahmad A, Abdullah SRS, Abu Hasan H, Othman AR, Ismail NI. 2021. Aquaculture industry: supply and demand, best practices, effluent and its current issues and treatment technology. *Journal of Environmental Management* 287:112271

[126] Aalto SL, Suurnäkki S, von Ahnen M, Tiirola M, Pedersen PB. 2022. Microbial communities in full-scale woodchip bioreactors treating aquaculture effluents. *Journal of Environmental Management* 301:113852

[127] Ahmed N, Turchini GM. 2021. Recirculating aquaculture systems (RAS): environmental solution and climate change adaptation. *Journal of Cleaner Production* 297:126604

[128] Widiasa IN, Harvianto GR, Susanto H, Istirokhatun T, Agustini TW. 2018. Searching for ultrafiltration membrane molecular weight cut-off for water treatment in recirculating aquaculture system. *Journal of Water Process Engineering* 21:133–142

[129] Pu C, Liu H, Ding G, Sun Y, Yu X, et al. 2018. Impact of direct application of biogas slurry and residue in fields: *in situ* analysis of antibiotic resistance genes from pig manure to fields. *Journal of Hazardous Materials* 344:441–449

[130] Zhang R, Wang X, Gu J, Zhang Y. 2017. Influence of zinc on biogas production and antibiotic resistance gene profiles during anaerobic digestion of swine manure. *Bioresource Technology* 244:63–70

[131] Song W, Wang X, Gu J, Zhang S, Yin Y, et al. 2017. Effects of different swine manure to wheat straw ratios on antibiotic resistance genes and the microbial community structure during anaerobic digestion. *Bioresource Technology* 231:1–8

[132] Sun W, Gu J, Wang X, Qian X, Tuo X. 2018. Impacts of biochar on the environmental risk of antibiotic resistance genes and mobile genetic elements during anaerobic digestion of cattle farm wastewater. *Bioresource Technology* 256:342–349

[133] Fang H, Han L, Zhang H, Long Z, Cai L, et al. 2018. Dissemination of antibiotic resistance genes and human pathogenic bacteria from a pig feedlot to the surrounding stream and agricultural soils. *Journal of Hazardous Materials* 357:53–62

[134] Tang T, Chen Y, Du Y, Yao B, Liu M. 2023. Effects of functional modules and bacterial clusters response on transmission performance of antibiotic resistance genes under antibiotic stress during anaerobic digestion of livestock wastewater. *Journal of Hazardous Materials* 441:129870

[135] Huang XF, Ye GY, Yi NK, Lu LJ, Zhang L, et al. 2019. Effect of plant physiological characteristics on the removal of conventional and emerging pollutants from aquaculture wastewater by constructed wetlands. *Ecological Engineering* 135:45–53

[136] Ma X, Li X, Li J, Ren JL, Chi L, et al. 2021. Iron-carbon could enhance nitrogen removal in *Sesuvium portulacastrum* constructed wetlands for treating mariculture effluents. *Bioresource Technology* 325:124602

[137] Zhang L, Lyu T, Vargas CAR, Arias CA, Carvalho PN, et al. 2018. New insights into the effects of support matrix on the removal of organic micro-pollutants and the microbial community in constructed wetlands. *Environmental Pollution* 240:699–708

[138] Tien YC, Li B, Zhang T, Scott A, Murray R, et al. 2017. Impact of dairy manure pre-application treatment on manure composition, soil dynamics of antibiotic resistance genes, and abundance of antibiotic-resistance genes on vegetables at harvest. *Science of The Total Environment* 581:32–39

[139] Tao CW, Hsu BM, Ji WT, Hsu TK, Kao PM, et al. 2014. Evaluation of five antibiotic resistance genes in wastewater treatment systems of swine farms by real-time PCR. *Science of The Total Environment* 496:116–121

[140] Yuan QB, Zhai YF, Mao BY, Schwarz C, Hu N. 2019. Fates of antibiotic resistance genes in a distributed swine wastewater treatment plant. *Water Environment Research* 91:1565–1575

[141] Huang L, Xu Y, Xu J, Ling J, Zheng L, et al. 2019. Dissemination of antibiotic resistance genes (ARGs) by rainfall on a cyclic economic breeding livestock farm. *International Biodeterioration & Biodegradation* 138:114–121

[142] Ma Z, Wu H, Zhang K, Xu X, Wang C, et al. 2018. Long-term low dissolved oxygen accelerates the removal of antibiotics and antibiotic resistance genes in swine wastewater treatment. *Chemical Engineering Journal* 334:630–637

[143] Huang X, Liu C, Li K, Su J, Zhu G, et al. 2015. Performance of vertical up-flow constructed wetlands on swine wastewater containing tetracyclines and *tet* genes. *Water Research* 70:109–117

[144] Yu J, Zhai Y, Che G, Lu Y, Zhang X, et al. 2026. Efficient removal of *Streptococcus suis* and its associated Tet(O) antibiotic-resistance genes by Fe doped carbon nitride photocatalytic activation peroxymonosulfate. *Separation and Purification Technology* 380:135566

[145] McCance W, Jones OAH, Edwards M, Surapaneni A, Chadalavada S, et al. 2018. Contaminants of Emerging Concern as novel groundwater tracers for delineating wastewater impacts in urban and peri-urban areas. *Water Research* 146:118–133

[146] Sun Y, Ren X, Rene ER, Wang Z, Zhou L, et al. 2021. The degradation performance of different microplastics and their effect on microbial community during composting process. *Bioresource Technology* 332:125133

[147] Núñez-Delgado A, Zhang Z, Bontempi E, Coccia M, Race M, et al. 2023. Editorial on the topic "new research on detection and removal of emerging pollutants". *Materials* 16:725

[148] Viau VE, Ostera JM, Tolivia A, Ballester ELC, Abreu PC, et al. 2012. Contribution of biofilm to water quality, survival and growth of juveniles of the freshwater crayfish *Cherax quadricarinatus* (Decapoda, Parastacidae). *Aquaculture* 324:70–78

[149] Liu FF, Lu T, Zhang YX. 2022. Performance assessment of constructed wetland-microbial fuel cell for treatment of mariculture wastewater containing heavy metals. *Process Safety and Environmental Protection* 168:633–641

[150] Zhou B, Luo J, Jin M, Xue N, He R, et al. 2025. Micropollutants removal from aquaculture water using layer-by-layer self-assembled nanofiltration membranes. *Water Research* 271:122933

[151] Sha S, Dong Z, Gao Y, Hashim H, Lee CT, et al. 2022. *In-situ* removal of residual antibiotics (enrofloxacin) in recirculating aquaculture system: effect of ultraviolet photolysis plus biodegradation using immobilized microbial granules. *Journal of Cleaner Production* 333:130190

[152] Xu C, Zhu C, Li Y, Zhang H, Lv W. 2024. Palygorskite-mediated simultaneous nutrient removal and antibiotic degradation from aquaculture wastewater in lab-scale constructed wetlands. *Chemical Engineering Journal* 499:156568

[153] Liu C, Lei J, Yu J, Chen J, Huang X, et al. 2025. The potential risk and sustainable reuse technologies of aquaculture wastewater: a review. *Current Pollution Reports* 11:39

[154] Cui E, Zhou Z, Gao F, Chen H, Li J. 2023. Roles of substrates in removing antibiotics and antibiotic resistance genes in constructed wetlands: a review. *Science of The Total Environment* 859:160257

[155] Gorito AM, Ribeiro AR, Gomes CR, Almeida CMR, Silva AMT. 2018. Constructed wetland microcosms for the removal of organic micropollutants from freshwater aquaculture effluents. *Science of The Total Environment* 644:1171–1180

[156] Deng YY, Zou MY, Liu W, Lian YL, Guo QM, et al. 2023. Antibiotic removal and microbial response mechanism in constructed wetlands treating aquaculture wastewater containing veterinary drugs. *Journal of Cleaner Production* 394:136271

[157] Deng Y, Liu W, Thi NT, Di HJ, Lian Y, et al. 2024. Exploring the efficiency of tide flow constructed wetlands for treating mariculture wastewater: a comprehensive study on antibiotic removal mechanism under salinity stress. *Water Research* 258:121738