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Microplastics and chemical contamination in aquaculture ecosystems: The role of climate change and implications for food safety—a review

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Abstract

The aquaculture industry is growing rapidly and plays a huge role in bridging the global demand gap for fish and other aquatic foods. It is a vital contributor of valuable nutrients and economic benefits. Aquaculture and fisheries provide a means of livelihood to an estimated 58.5 million people globally, according to the United Nations Food and Agriculture Organisation. However, the sector is impacted by the ubiquity of microplastics and toxic chemicals. Although many studies have reported plastic pollution in the aquaculture environment, less attention has been paid to the coexistence of toxic chemicals with plastic particles and the role of climate change in aquaculture food contamination. This review evaluates the occurrence of microplastics in organisms, feeds, water, and sediment in the aquaculture ecosystem and the detection and hazardous effects of toxic chemical contaminants. We also highlight novel insights into the role of climate change in plastic and chemical contamination of aquaculture organisms and ecosystems. We report that the extent of aquaculture's contribution to global climate change and global plastic pollution is yet to be adequately quantified and requires further investigation for appropriate risk assessment and prevention of food safety crisis. Possible mitigation strategies for the highlighted pollution problems were suggested, and some identified gaps for future research were indicated. Overall, this work is one of the first efforts to assess the influence of climate change on aquaculture food contamination, emphasising its effects on food safety and ecosystem health.

Keywords Blue foods, Sustainability, Fish feed, Food web, POPs, SDGs

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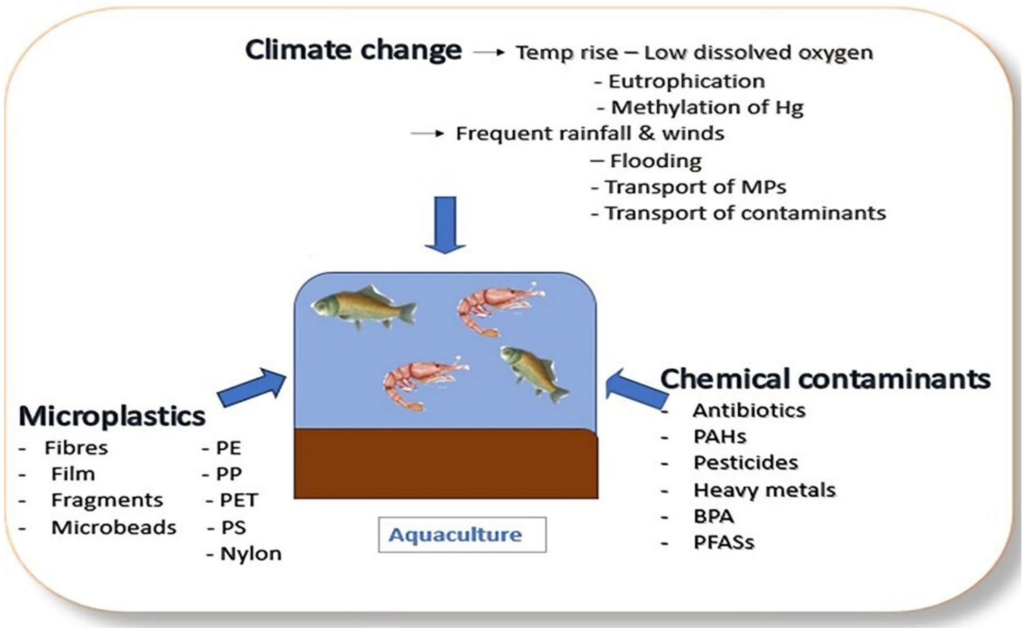
Graphical Abstract



Introduction

Plastic materials' low cost, flexibility, lightweight, water imperviousness, and durability have made them almost indispensable in everyday use. However, associated aesthetic, persistence, biological, chemical, and health problems arise from the indiscriminate use and disposal of plastics [30, 32]. The plastic industry's global production has experienced significant growth, going from 1.5×10^6 Mt in the 1950s to approximately 350×10^6 Mt in 2017, of which millions of tons of plastic waste are discarded into the environment annually [80, 81, 88]. Plastic debris in the environment is classified by sizes; as large plastics are subjected to environmental factors such as mechanical abrasion, wave action, exposure to UV radiation and heat, they become brittle and breakdown to smaller sizes. Megaplastics are >100 mm, macroplastics range from 25 to 100 mm, mesoplastics are 5–25 mm, microplastics (MPs) refer to plastic particles that are greater than 1 µm but <5 mm, while nanoplastics are <1 µm in size [4]. Micro- and nanoplastics (MNPs) are emerging contaminants of concern because of their aggregation in many environmental matrices, including marine and freshwater, air, soils, sediments, and living biota. In addition, they provide active transportation for other environmental contaminants [33]. Microplastics found in the aquatic environment could be primary microplastics, which are either manufactured as less than 5 mm or are formed during intentional use, or secondary microplastics, which are formed by the fragmentation of larger plastics during environmental weathering [30, 32, 71]. As depicted in Fig. 1, plastic pellets, paint, wastewater, sewage sludge, artificial turf, rubber roads in cities, plastic running tracks in schools, and tyre wear particles from vehicles are primary sources of environmental microplastics. Secondary sources include municipal wastes like plastic bags and bottles, fishing wastes, farming film, and other large-sized plastic wastes [5]. Any increase in environmental microplastic concentrations increases the probability of ecosystem exposure and the possibility of contact, ingestion, and hazardous impacts across food webs [18]. A major factor in the growing amount of microplastic pollution in the aquatic ecosystem is the use of plastic mulch and sludge application in agricultural lands, textile production, everyday consumer goods, cleaning agents, and health and personal care products [82]. Aquatic animals, including aquaculture organisms, are exposed to MPs which may be incorporated through their gills and digestive tracts, ingestion of contaminated smaller creatures, or feeds. MPs may also adhere directly to the bodies of fish [19, 124]. Studies have indicated the uptake and accumulation of MNPs in aquatic species with attendant ecotoxicological effects such as oxidative stress, neurotoxicity, growth retardation, tissue damage,

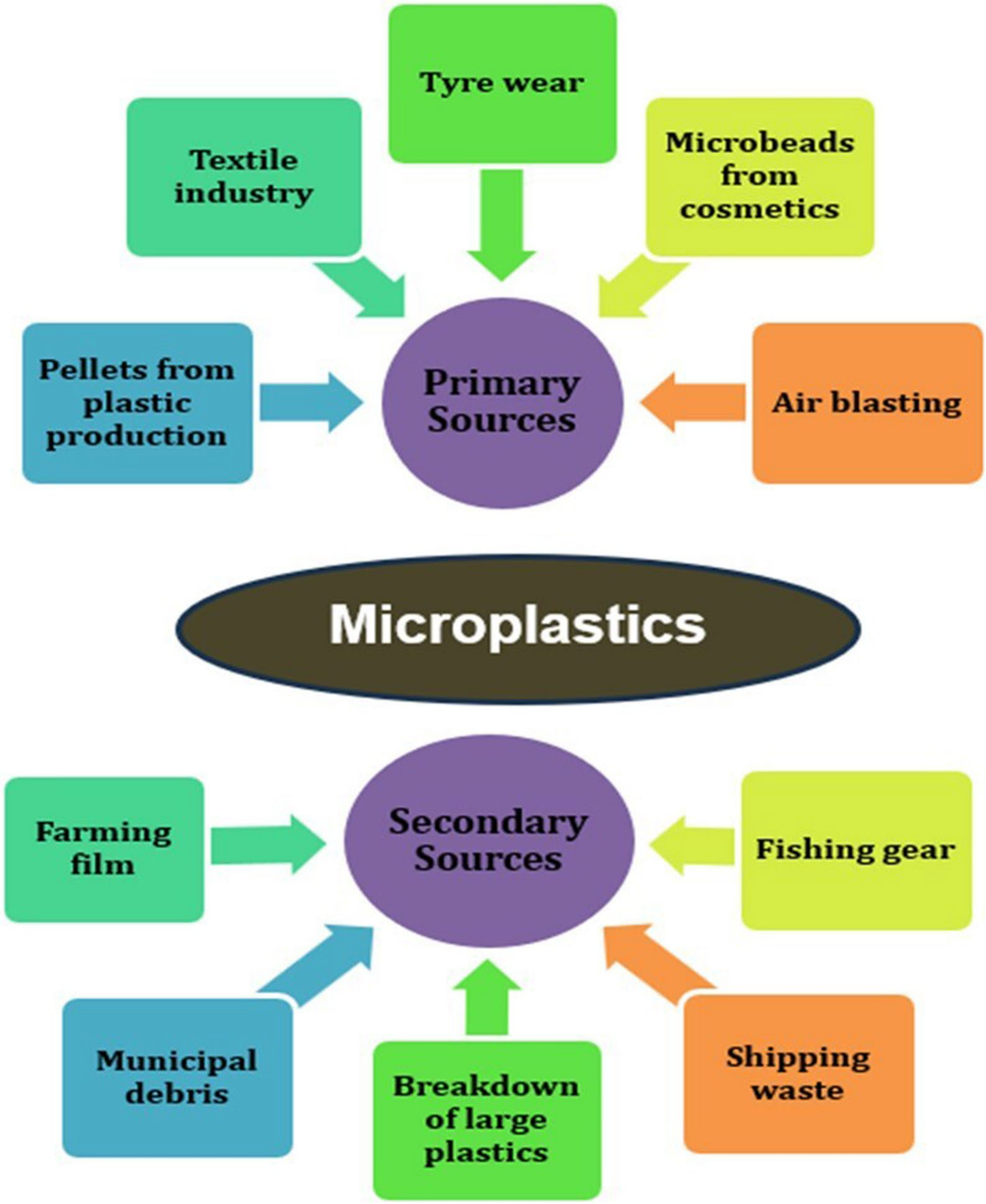


Fig. 1 Sources of environmental microplastics

and behavioural abnormalities [12]. Owing to the widespread use of plastics in manufacturing, packaging, agriculture, and other industries, they can be found in a variety of environmental matrices, including lakes, rivers, canals, sediments, and seas [81], and the aquaculture ecosystem is not exempted.

Aquaculture (aquatic agriculture) involves the breeding, rearing, and harvesting of fish, shellfish, algae, and other organisms in all types of water environments. Apart from food production, aquaculture is also used to produce other commercial products, restore habitat, replenish wild stocks, and rebuild populations of threatened and endangered species [83]. It is the production of aquatic organisms under controlled conditions throughout part or all of their lifecycle. Its development can help meet future food needs and ease the burden on natural resources [103]. According to the Food and Agriculture Organisation of the United Nations, 90% of monitored fish stocks are fully or overexploited [28]. Fish and other aquatic foods (also called blue foods) are a primary source of protein and other essential nutrients. They contain micronutrients such as zinc, calcium, phosphorus, iron, omega-3 polyunsaturated fatty acids, vitamin A, and vitamin D. The consumption of aquatic food is critically important for foetal neurocognitive development and adult cognitive and cardiovascular health [29]. The growing demand for fish and other seafood raises questions about the sustainability of marine fish and other natural harvesting sources. The global demand for aquatic foods is expected to double by 2050, according to a series of scientific studies released by the Blue Food Assessment. The report indicated that increased aquaculture production, as opposed to capture fisheries, will primarily meet this demand [13]. It is the world's fastest growing food industry, with over 600 aquatic species farmed globally [28]. Global aquaculture production retained its growth trend in 2020 in spite of the worldwide spread of the COVID-19 pandemic [29]. A recent study found a positive association between aquaculture production and aquatic food consumption at the national scale [100]. For aquaculture to meet the requirements of the future, it must be practised in a manner that fulfils the economic, social, and environmental pillars of sustainability. That is, it must be a viable business opportunity, contribute to community health and well-being, and not create significant ecosystem disruption. However, disruptions may occur in the form of plastic and chemical contamination and climate change effects. A number of studies have discussed the occurrence of microplastics and their effects on the aquaculture ecosystem and organisms [47, 49, 62, 63], but the co-occurrence of chemical contaminants with microplastics and the role of climate change in aquaculture food contamination is less considered. The changing climate has been reported to induce critical microplastic pollution and sediment resuspension in shallow lakes, which in turn exacerbate eutrophication and alteration of the aquatic ecosystem [123]. Korez et al. [56] reported that sites close to aquaculture farms and facilities showed a prevalence of microplastic contamination. Furthermore, current evidence suggests that farmed fish typically contain more microplastic than wild-caught fish [110] and the changing use of chemicals in agriculture and aquaculture [15] are impacting the ecosystem, threatening food safety. In addition to fishing, fisheries, and shipping, aquaculture has also been identified as a sea-based source of plastic pollution [37]. This review therefore elucidates the co-occurrence of microplastic fibres, films, fragments and microbeads and chemical contaminants such as antibiotics, polycyclic aromatic hydrocarbons, pesticides, bisphenol A, per and polyfluoroalkyl substances and heavy metals in aquaculture feed and environment. We also highlight novel insights into the role of climate change through temperature rise, frequent rainfall and strong winds in aquaculture food contamination. The goals of the study were to (i) summarise the available information on the occurrence of microplastics in aquaculture organisms and environment; (ii) highlight the coexistence of plastics particles with chemical contaminants in the aquaculture ecosystem; and (iii) emphasise the role of climate change in aquaculture chemical and plastic pollution and food contamination, and consequent effects on food safety and ecosystems health.

Methodology

Data for this review were collected from original research articles, reports and reviews from databases including ScienceDirect, Web of Science, PubMed, Frontiers and online reports posted by United Nations Food and Agriculture Organisation. Based on the objectives of this article to identify and summarise studies that advance our understanding of microplastics and chemical pollution and how climate change drives aquaculture food contamination, the keywords/phrases used in the search included 'microplastics in aquaculture' 'toxicity of microplastics', 'aquaculture plastic pollution', 'chemical pollutants in aquaculture', 'climate change and aquaculture', and 'climate change and aquaculture food contamination'. The search was limited to studies that were published between 2014 and 2024, to track the progress in research in recent years. However, a few older studies were considered for other relevant information. Over 2000 research publications were generated from the searches, but the articles were screened based on provision of useful parameters such as adequacy of analytical information and relevance to the discussion on microplastic pollution, chemical pollution, microplastics detection in aquaculture ecosystem, ecotoxicological effects of microplastics and climate change in aquaculture environment. A total of about 190 relevant publications were eventually used for this review. The summary of the literature search strategy is presented in Fig. 2.

Overview and sources of microplastics in aquaculture

Aquaculture extensively uses plastics for equipment and packaging, with plastic materials used in everything from polystyrene foam-filled fish cage collars and polymer-coated cage nets to plastic harvest bins and feed sacks, fishing nets, ropes, and foam buoys. These plastics degrade into smaller particles or are lost into the environment as a result of extreme weather, poor waste management, installation wear, and failure resulting from poor siting or lack of maintenance [62, 63]. High-density

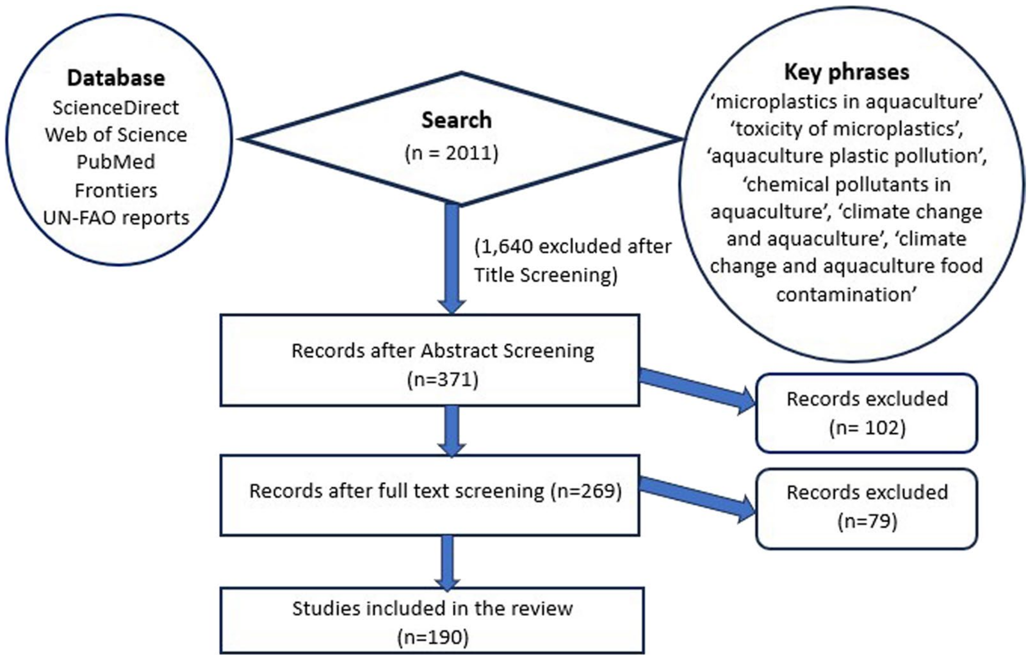


Fig. 2 Flow diagram for literature search

polyethylene, which is used for buoys, floats, and storage tanks, is tough and chemically resilient, so it takes longer to fragment and abrade but can weather and lead to microplastic formation [47]. Expanded polystyrene (EPS), which is used for insulation and fish boxes, is extremely light and buoyant, so it can accumulate on beaches but breaks easily into smaller pieces [11]. Polyvinyl chloride (PVC), is a material that is frequently used in pipe and valve fittings for offshore cages. It is very durable but is not often recycled and requires a long time to abrade. The plastic materials (such as nylon, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), or polyester) used to make ropes, cords, and nets differ in terms of their strength, elasticity, and rate of fragmentation and breakdown [47]. The presence of microplastics has been reported in various matrices in aquaculture, including feeds, surface water, sediment, and organisms. Bordós et al. [125] found polypropylene and polystyrene (PS) microplastics in fish ponds in the Carpathian basin, Europe, with the indication that fish ponds may act as a deposition area for MPs. A recent study reported that microplastics (PE, polytetrafluoroethylene (PTFE), PS, and polyamide (PA)) were present in head samples and the skin and muscle of sea bass samples. The results also showed lower concentration of MPs in the aquaculture tanks than in the source water inlet but purification treatment of the source water was effective in significantly reducing the MPs released into the tanks. However, new MPs were detected in the aquaculture tanks, which was indicative of contamination from fish feed [25]. Further evidence of MP detection in aquaculture environments is shown in Table 1. Fibres and fragments are the most detected particle types, while PE and PP are the most common polymer types.

Land-based sources remain the major origin of plastic pollution in marine and freshwater environments, but a recent study has indicated that the contribution of aquaculture activities to microplastic pollution could be substantially underestimated [121, 122]. The sources of plastic pollution in aquaculture systems are highlighted as follows:

Fish feed

Small pelagic fish are more susceptible to accumulating microplastics [66]. These small fish are typically caught in fishing nets as non-target species and used as the main ingredients in fish feed for aquaculture and livestock animal production. Fish feed is rich in protein and is mainly produced with small pelagic species, by-catches, excess allowable catch quota trimmings, and fish processing wastes. A total of up to 81% of non-food fisheries are used to produce fish feed [29]. Some of the species that are used for producing fish feed are Peruvian anchoveta (*Engraulis ringens*), blue whiting (*Micromesistius poutassou*), lesser sand eels (*Ammodytes tobianus*), menhaden (*Brevoortia tyrannus*), Atlantic herring (*Clupea harengus*), mackerel, capelin, and Pacific

Table 1 Detection of microplastics in aquaculture farms

Matrix	Particle abundance	Particle size	Dominant particle types	Polymer type	Analytical methods	References
Sediment Water	47 ± 4.875 particles/g 127.92 ± 14.99 particles/100 L	0.05–0.5 mm	Fibres	Nylon, PE, PP. PS	SEM, FTIR	[45, 46]
Crab Water Sediment	23.9 ± 15.9 items/individual 4.4–10.8 items/L 28.6–54.3 items/100 g	100–300 μm	Fibre, grain, film, fragments	PE, PP, PVC, PET	ATR-FTIR	[116]
Sediment Water	3.33–137 items/kg 16.67–100 items/L	0.5–1 mm	Film, fibre, microbeads, foam	PP, PE, PET	FTIR	[45, 46]
Fishmeal	550 ± 45.45 to 11,600 ± 56.1 MPs/kg	14–4480 μm	Filament, film	PP, Nylon 66, PET, PS	KOH digestion, FESEM–EDS, FTIR	[75]
Fishmeal	1070–2000 particles/kg (including other anthropogenic particles)	25–100 μm	Fibres, fragments	PA, polyester, PP, PS	10% KOH digestion, FTIR	[107]
Fishmeal	5.5 ± 1.6 particles/g	500–1000 μm	Fibres	Cellophane, PP, PET	Microscope, μ-FTIR	[108]
Sediment	2767 ± 240–2833 ± 176 items/kg	0.1 μm–5 mm	Fibres, fragments	PE, PP	Raman	[59]
Fish Water Mussels	7.1 items/fish 523 items/m^3 0.36 ± 0.81 items/individual	0.5–5 mm	Foam	PS	Raman, μ-FTIR	[62, 63]
Fishmeal	12.9 mg/kg	80–1550 μm	Fibres	PS, polyolefin, PET	Gravimetry, SEC-UV, solvent extraction, HPLC	[20]
Fishmeal	0–526.7 particles/kg	Average of 4.2 ± 0.3 mm	Fragments, fibres, filament, film, foam	PE, PP, polyacrylic acid, PET	Microscope, Raman	[41]
Water	42.1 particles/L	<100 μm	Fibre	PP, PE	Microscope, FTIR	[68]
Fish	13.54 ± 2.09–22.21 ± 1.70 items/individual	<5 mm	Fibre, fragments	cellophane	Stereomicroscope, FTIR	[124]

sardine (*Sardinops sagax*). Feeding farmed fish regularly with MP-contaminated feed makes fishmeal and fish feed entry points for microplastics into aquaculture species. In a recent study, MP particles were found in all five commercially produced fish feeds purchased in Bangladesh [75]. Another study reported the detection of anthropogenic particles, including microplastics and cellulosic microfibres, in all ten aquaculture feeds tested, with an average of 1070–2000 particles per kg across fishmeal and soybean meal [107]. The level of plastic pollution in fish feed corresponds with the feeding behaviour of the organism used for the production of the feed. For instance, feeds containing a high percentage of carnivorous fish species, such as eels, were found to have a substantially higher risk of plastic intake than others [41]. These studies show that anthropogenic particle contamination of aquaculture feed introduces an additional exposure pathway for farmed species, which may have adverse effects on fish health as well as nutritional value, profitability, and ultimately food security and safety.

Abandoned or decommissioned coastal pond farms

There are many abandoned aquaculture farms in different parts of the world, and this is a growing issue. When this happens, bulky items such as pond liners and other plastic infrastructure are left to disintegrate and disperse into the environment. Abandoned, lost, or otherwise discarded fishing gear (ALDFG), also called "ghost gear", constitutes a significant part of marine plastic pollution in the world's oceans and seas [36]. Up to 46% of the species on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species have been impacted by ALDFG, mainly through entanglement or ingestion, which impacts biodiversity [29]. Examples of ALDFG include trawls, gill nets, handlines, and longlines. PVC tubes, net caps, plastic bands, zip ties, oyster bags, and nets on shellfish beds have been recorded [67]. Over time, these materials disintegrate into secondary microplastics. In Thailand, after the introduction of intensive shrimp aquaculture between 1972 and 1987, up to 80% of farms were forced to abandon their operations after a few years due to the high mortality rates of shrimp recorded [22]. Several abandoned aquaculture farms also exist in China [16, 17], the Philippines [69], as a result of devastating tsunamis, and Nigeria [52], largely due to socio-economic factors. Some of the pathways through which plastics are introduced into the aquaculture ecosystem are summarised in Fig. 3. As shown in Fig. 3, both marine and freshwater aquaculture are affected by the influx of microplastics from ALDFGs, feeds, poorly installed plastic facilities, land sources and climate related releases [29] to which aquaculture products are exposed. The final step before aquaculture products are moved from the ecosystem to retailers and consumers is packaging. Aquaculture products are often packaged in corrugated plastic boxes, expanded polystyrene boxes, and plastic trays [111]. Research has indicated that microplastic fibres can be emitted from plastic packaging materials, with polystyrene plastics having the maximum release abundance [23]. In another study, polystyrene packaging was found to release microplastics to rainbow trout fillet, depending on the storage temperature [3].

Poor waste management

Aquaculture may generate significant amounts of plastic waste, including feed sacks, plastic-wrapped consumables, and disposable equipment such as gloves made out of plastic and plastic-coated. These different waste streams require responsible disposal and a safe and secure collection of waste that is not vulnerable to scavengers or blown away by strong winds. Since the recycling of aquaculture plastic waste is complicated and limited, waste management can be challenging, especially when operations are taking place at sea (e.g., on cage sites) or on large, often exposed coastal pond sites [47].

Plastic release due to climate and weather issues

The push to move aquaculture further offshore means that sea cages are often fixed in exposed sites that are vulnerable to intense winds and high waves. The increasingly unpredictable weather caused by climate change could exacerbate this issue. Coastal ponds are susceptible to storm surges and inland flooding, which can wash unsecured equipment into the sea and potentially damage adjacent coral reefs, mangroves, and coastal wetland areas. Aquaculture infrastructure is impacted by sea level rise, sea surges, typhoons, and rainfall intensity, which results in water and food security issues from changing rainfall patterns and ocean acidification [6]. The well-being of the system is also affected by rising temperatures, peak wind speeds, and changes to ocean circulation patterns. Unfortunately, the magnitude and frequency of these hazards are expected to increase, especially impacting the most vulnerable populations such as small-scale fish farmers. Microplastics have been found in cloud water samples in China [113]. The researchers warn that airborne MPs could affect cloud formation, global temperatures, and weather.

Poor installation and maintenance of plastic equipment and materials

In selecting a site for aquaculture, a number of factors must be considered including, ecological, biological, operational, and socio-economic factors [57]. The supply of water, water quality, climate, land, hydrological and soil characteristics are crucial ecological factors that will determine the success or otherwise of the system. The adequacy of the equipment for the environment into which it is placed, and the subsequent installation,

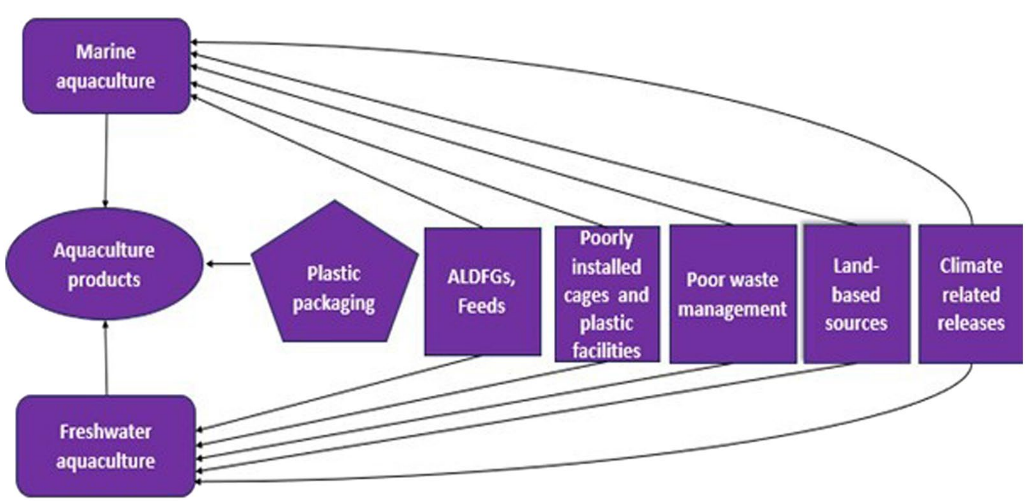


Fig. 3 Pathways by which microplastics enter aquaculture products and ecosystem

maintenance, and replacement will influence (i) how much plastic will abrade (leading to secondary microplastic formation) and (ii) the risk of equipment failure and loss of plastic components to the aquatic environment.

Plastic flow from the external environment

Plastic pollution in surrounding land and water finds its way into the aquaculture ecosystem. Several studies have demonstrated that microplastic pollution of aquaculture areas in estuaries and coastal areas near estuaries is associated with a high abundance of microplastics in local rivers and freshwater sources [58, 68]. Land pollution also impacts aquaculture ecosystems. For instance, due to the accumulation of garbage around, high microplastic abundances (103.8 ± 20.7 and 90.7 ± 17.4 particles/L) were found in the water of Marunda and Muara Kamal aquaculture ponds [89]. Although aerial deposition of MPs has been widely reported in many environments, it is yet unknown whether this avenue is a significant contributor to aquaculture microplastic pollution.

Chemical contaminants in aquaculture

Like other parts of the environment, the aquaculture ecosystem is affected by many environmental pollutants. Some of the pollutants are airborne, present in the surrounding water, or in soil and sediment. Sediment is a known sink for heavy metals and organic pollutants [8]. Some pollutants occur as natural components of soil or sediment, while others are introduced by human activities around the ecosystem. The pollutants that bind to sediment particles may be released into the water by resuspension during massive fish activities. Some of the pollutants are also able to bind to plastic particles and be transported within and outside the aquaculture environment. For example, antifoulants, antibiotics, parasiticides, anaesthetics, and disinfectants are employed in salmon aquaculture [15]. These chemicals are regulated differently in each country, as are their uses and possible side effects. The ecological balance of aquatic ecosystems can be disrupted due to the negative responses of primary producers like algae when exposed to various contaminants, including pesticides, heavy metals, industrial chemicals, and synthetic nano/microparticles [60]. A recent study demonstrated the significant ways in which aquatic ecosystem imbalance can be induced by anthropogenic inputs of chemical contaminants [60]. The study showed that Bisphenol A can negatively impact algae by inhibiting biochemical and physiological processes, with effective concentration varying from 1.0 to 100 mg/L. Furthermore, the combined contaminant exposure of per- and polyfluoroalkyl substances concentrations up to 1000 ng/L, leads to significant toxic effects and is unsafe for the ecosystems. Per- and polyfluoroalkyl substances could impede algal growth through damage to the photosynthetic processes, inhibition of deoxyribonucleic acid replication, and reactive oxygen species metabolism. The ecotoxicity of chemicals to algae is influenced by chemical, biological, and physical factors, creating complex effects on biological communities [60]. Some of the chemical contaminants which have been reported in the aquaculture environment are discussed as follows:

Antibiotics

Wastewater from aquaculture was shown to have negative environmental impacts because of antibiotic residues and other chemicals. Antibiotics are designed to inhibit growth (bacteriostatic activity) and kill pathogenic bacteria (bactericidal activity). They are orally administered to aquaculture animals against lice, local eutrophication, and oxygen depletion. However, shrimp aquaculture source water and wastewater were found to contain antibiotic resistance genes (ARGs) [98, 119]. Similarly, MPs were reported to accumulate ARGs and harbour pathogens in an aquaculture ecosystem, posing potentially critical health and ecological risks [112]. An antibiotic resistance gene confers resistance to antibiotics when it is present or increases susceptibility to antibiotics when it is absent, which has led to the suggestion that there is a high risk that these genes will spread to bacteria that cause human infections [72]. When transferred to humans, ARGs lower the ability to fight infections. A recent study found that antibiotics selectively adsorb on aged MPs originating from aquaculture, and risk assessment indicated potential health risk to humans consuming the seafood contaminated by antibiotics-laden microplastics [117].

Polycyclic aromatic hydrocarbons (pahs)

PAHs are a group of organic compounds with two or more fused aromatic rings that are highly ubiquitous, persistent, and hydrophobic. PAHs have carcinogenic, mutagenic, and toxic effects on organisms. They are mainly derived from two sources: pyrogenic and petrogenic. Pyrogenic PAHs are formed from fossil fuel combustion, waste incineration, wood, tobacco, biomass burning, and asphalt production, while petrogenic PAHs are associated with crude and refined oil. Pyrogenic PAHs are characterised by 4–6 aromatic rings (high molecular weight), and petrogenic PAHs mainly consist of 2–3 rings (low molecular weight). Atmospheric PAHs (gaseous phase as aerosols) are deposited in water, soil, and plants in the particulate phase through dry and wet deposition processes [1]. The accumulation of PAHs in soil or sediment is responsible for the further transport of pollution to surface water, groundwater, plants, aquatic organisms, and food. Furthermore, human long-term exposure to PAHs could induce oxidative stress, immune responses, cataracts, kidney and liver damage, and functional abnormalities of the respiratory system. Eighteen PAHs detected in farmed giant sea perch were reported to have a mean concentration of 573.66 ± 47.56 ng/g dry weight, but the concentration was within acceptable limits recommended by USEPA [76]. Another study assessed USEPA-priority PAHs in Taiwanese aquaculture-farmed fish (*Mugil cephalus* and *Oreochromis mossambicus*) and shellfish (*Corbicula fluminea Formosa* and *Meretrix lusoria*). The level of PAHs detected ranged from 20.0 ± 0.8 to 43.0 ± 11.3 ng/g wet weight and posed a low hazard risk to consumers of the farmed fishes [53]. However, farmed fish, shrimps, and crabs from the Yellow River Estuary of China were also reported to accumulate 3-ring PAHs, and risk assessment indicated that PAHs in mature aquatic products posed carcinogenic risks to humans [119]. In the few available studies, low-molecular-weight PAHs were dominant, indicating higher petrogenic inputs. Marine oil spills could be responsible for the presence of the petrogenic PAHs in the tested ecosystems. Additionally, many studies have demonstrated the adsorption and transport of PAHs by microplastics [21, 34, 53]. Overall, this suggests that plastic particles may continue to retain and transport PAHs within and outside the aquaculture ecosystem. Contamination should be monitored to keep their levels within acceptable limits.

Pesticides and herbicides

The use of herbicides and pesticides for the control of weeds, pests, algae, and bacteria in crop farming is a common practice in agriculture. In applying herbicides and pesticides, residues accumulate in the crops and soils. The contaminated crops are processed into fish feed for commercial aquaculture farms. Despite the ban on organochlorine pesticides in many countries, they are still detected in environmental samples [54]. Organophosphorus pesticides such as chlorpyrifos-methyl (CPM) were detected in feeds used in Atlantic salmon aquaculture [86]. CPM is known to be highly toxic to fish. In commercially available Atlantic salmon feeds surveyed in 2017, the levels of CPM reported ranged from 11 to 26 μg/kg [95]. A study detected the presence of atrazine (a herbicide) in farmed catfish and fish feed in Nigeria, with mean concentrations ranging from 1.3–1.5 to 1.4–1.8 μg/kg in fish feed and catfish, respectively [85]. Since microplastics are present in the aquaculture ecosystem, they may also act as vectors of organochlorine pesticides (OCPs) and dichlorodiphenyltrichloroethane (DDTs) [33, 96, 120].

Heavy metals

Heavy metals are naturally occurring elements that have a high atomic weight and a density at least five times greater than that of water. Heavy metals are naturally found throughout the earth's crust, but most environmental contamination and human exposure result from anthropogenic activities such as mining and smelting operations, industrial production, and domestic and agricultural use of metals and metal-containing compounds [101]. Metal corrosion, atmospheric deposition, soil erosion of metal ions and leaching of heavy metals, sediment resuspension, and metal evaporation from water resources into soil and groundwater are also sources of environmental contamination by metals. Heavy metals are also considered trace elements because of their presence in trace concentrations (ppb range to less than 10 ppm) in various environmental matrices [101]. Sediments in aquatic ecosystems are known repositories as well as sources of several inorganic contaminants, including toxic heavy metals [8]. Aquaculture and agricultural practices contribute to worldwide metal pollution due to diverse applications of metals in feed additives, organic and inorganic fertilisers, pesticides, and anti-fouling products [15]. Potentially toxic metals such as Cd, Cr, Pb, Cu, Zn, Mn, As, Hg, and Ni, due to their long-term persistence in the environment, allow them to accumulate in the food chain. Heavy metal toxicity negatively affects the growth, reproduction, and physiology of fish and other aquatic organisms, which threatens sustainable production in the aquaculture sector. An assessment of metal contamination in aquaculture showed higher levels in plastic materials than in the surrounding water [74], which suggests that inherent metal levels in plastics are significantly high. The presence of heavy metals such as Hg, Cd, Cu, and Zn was reported to promote antibiotic resistance through co-selection in aquaculture soil and water [94]. These studies suggest that the coexistence of plastic particles and potentially toxic metals presents a higher risk of toxic effects on organisms and the aquaculture environment.

Bisphenol A (BPA)

BPA is an endocrine disrupting chemical. With its two benzene rings and two (4,4′)-OH substituents, BPA fits within the binding pockets of both oestrogen receptor (ER)α and (ER)β. BPA also binds to several organ receptors, including the oestrogen-related receptor γ as well as the aryl hydrocarbon receptor [55]. The large number of receptors and signalling pathways affected by BPA led the US National Toxicology Programme (NTP) to assign it the third highest toxicological priority index (TPI) score of more than 300 chemicals examined [91].

BPA is used primarily in the production of polycarbonate plastics as an additive to act as an antioxidant, hardening agent, or a stabiliser. Examples of such plastic products are shatterproof windows, water bottles, toys, and epoxy resins for the coating of metal food cans, bottle tops, and water supply pipes. The primary source of exposure to BPA in humans is through diet. Exposure is also possible through air, dust, and water. BPA can leach into food and water from protective coatings, especially at high temperatures [78]. Low levels of BPA exposure have been shown to induce adverse health effects in both animal and human studies, including obesity, metabolic disease, impaired glucose tolerance, cardiovascular disease, and many more [91]. A study reported the levels of BPA in fish species, *T. blochii* (0.322 ng/g), *L. calcarifer* (0.124 ng/g), and *L. campechanus* (0.023 ng/g) from aquaculture farms in Malaysia [50]. Another study surveyed freshwater and marine water cultured green mussels (*Perna viridis*) for the occurrence of BPA and high levels of BPA, and 17*β*-estradiol were detected in the mussels and the surrounding water samples. Furthermore, the mature green mussels were found to accumulate higher concentrations of BPA than the juveniles [84]. In a recent study simulating marine conditions, Gulizia et al. [39] reported that the leaching of BPA from PVC microplastics accelerates at higher temperatures, and smaller plastic particles diffuse BPA at a much higher rate than larger particles. The study suggests that leaching will be further exacerbated by rising and fluctuating water temperatures, such as those predicted with global warming.

Per and polyfluoroalkyl substances

Perfluoroalkyl and polyfluoroalkyl substances (PFASs), otherwise known as 'forever chemicals', are emerging environmental contaminants that have gained considerable attention among researchers in recent times. They are chemically similar to persistent organic pollutants (POPs), except that they are hydrophilic compounds. They are persistent and bioaccumulative and have been detected in matrices like food contact materials, water, air, sediment, and soil in different parts of the world [16, 17, 106]. PFASs were found in the effluent and influent water, and sediment of bullfrog aquaculture ponds, with concentrations ranging from 50.26 to 364.25 ng/L and 2.89 to 162.26 ng/g·dw, respectively. Bullfrog tissues also had concentrations ranging from 3.36 to 84.07 ng/g dw [99]. Another study surveyed PFAS in farmed and wild-caught marine fish and found that the levels of PFAS (<13 ng/g) in farmed fish was lower than in wild-caught fish [118]. Although the studies showed that frequent consumption of the farmed animals did not pose any severe health risks on consumers in terms of PFASs, it is important to continue to monitor the chemicals to ensure food safety.

Impact of climate change on microplastics and chemical contaminants

According to the Intergovernmental Panel on Climate Change (IPCC), climate change refers to any change in climate over extended periods due to natural variability or as a result of human activities. Greenhouse gas emissions have a significant effect on Earth's climate, raising average global temperatures and causing global warming. Greenhouse gases (GHGs) such as water vapour, CO_2, CH_4, O_3, chlorofluorocarbons (CFCs), and N_2O, trap photons of wavelengths in the infrared (IR) region and are therefore important temperature regulators of our atmosphere [14]. This results in the greenhouse effect, which is necessary to keep the earth's climate comfortable [77]. However, since the industrial revolution, the concentrations of most GHGs have substantially increased in the atmosphere, thereby increasing the amount of trapped heat and emitting ultraviolet radiation, resulting in climate change [14]. Human activities including power generation, industrial production and transportation utilising fossil fuels such as coal, oil or gas which produces CO_2 and N_2O contributes to climate change. Instances of mangrove clearing for the purpose of aquaculture have also reduced carbon sinks, thereby increasing the persistence of GHGs [38, 92]. These changes are evidenced by rises in average temperatures, more variable weather patterns, rising sea levels, warmer oceans, frequent forest fires, and extreme events such as floods, storms, cyclones, landslides, and droughts [10]. For instance, the negative effects of GHG emissions and climate change indirectly affect aquaculture production by influencing output and consumption [79].

The role of climate change in aquaculture food contamination is an emerging topic of discourse; hence, more research is still required to improve knowledge and develop mitigation and risk assessment strategies. Like most sectors, aquaculture production is susceptible to the impact of climate change occasioned by changes in weather patterns such as temperature rise, intense and frequent rainfalls and strong winds, leading to floods and transport of microplastics and chemical contaminants (Fig. 4). Several other factors have been suggested to drive the transport of plastic from land into the ocean, including river hydrodynamics, wind speed and direction, river morphology, and tidal dynamics [26], however, the focus here is on flood-mediated transport. According to estimates by Hurley et al. [48], the 2015 floods in the United Kingdom caused a 70% transport of microplastics in river sediments. Although the extent

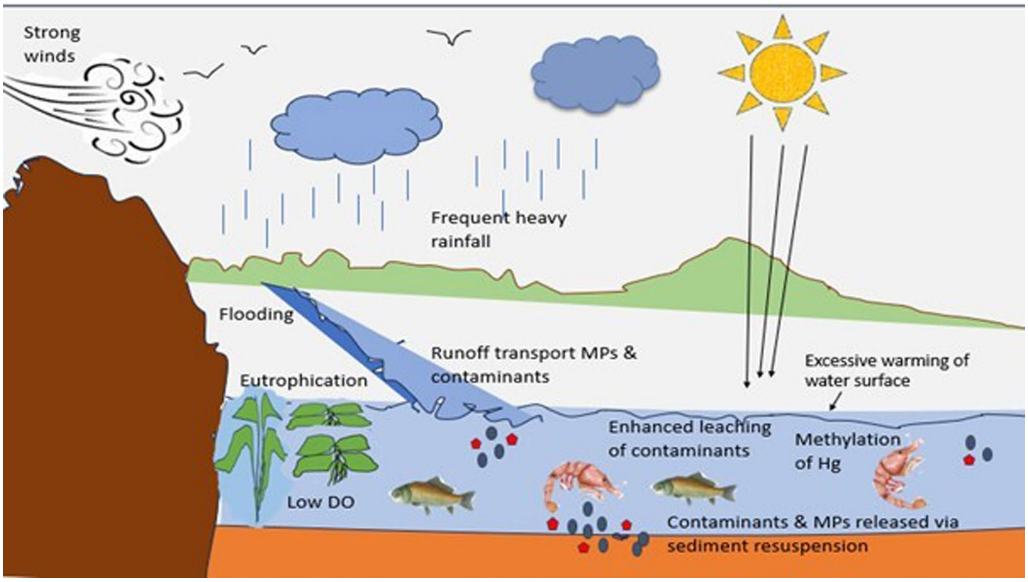


Fig. 4 The role of climate change in aquaculture food contamination

of MPs transport was not known, it was determined that microplastic contamination is efficiently flushed from river catchments during flooding. In a study by Gündoğdu et al. [40], it was reported that the amounts of microplastics carried into the North-East Mediterranean sea increased by 14-fold after multiple flood events. Another study by van Emmerik et al. [105] demonstrated that fluvial floods drive macroplastic (>2.5 cm) transport and accumulation in river systems. Organic pollutants and metals bound to plastic and sediment can also be transferred by floods and constitute a significant threat to the environment [70]. Climate change-related flooding also transports more microplastics and causes sediment resuspension in shallow lakes [123]. Increased temperatures cause a lower solubility of oxygen in water [low dissolved oxygen (DO)] and encourage the growth of bacteria and parasites, which is damaging to organisms and the ecosystem. Warmer oceans and surface waters facilitate the methylation of mercury and subsequent uptake of methyl mercury (a neurotoxin) in fish and other aquatic organisms, which in turn increases human dietary exposure to methyl mercury [121, 122]. Frequent and intensive forest fires result in the release of POPs like PAHs and dioxins, which can be aerially deposited into aquatic environments [27]. Because of drought or excessive rainfall, the use of fertilisers, pesticides, and veterinary medicines is changing. Excess and residues of these chemicals can be carried by floods and stormwater into aquaculture ponds leading to nutrient enrichment and eutrophication. Excessive growth of algae and plankton in a water body are indicators of the eutrophication process. Harmful algal blooms (HABs) have a greater impact on aquaculture than on wild capture fisheries [102]. This is because cultivated species are unable to relocate from areas where HABs are present and could die from toxins or water deoxygenation. HABs are frequently found in estuaries or coastal waters which are used for aquaculture, and global aquaculture growth has been found to be closely associated with rising instances of toxic algal blooms [43, 102]. Increased winds and air currents, such as the Gulf Stream, may also impact the global distribution of POPs and microplastics [104]. These factors, if unabated, will cause a decline in fish survival, impact natural food sources, and affect the sustainability, growth, and reproductive success of wild populations and farmed species.

Aquaculture is also identified as a contributor to climate change. According to Ahmed et al. [2], aquafeeds contribute the largest GHG emissions in aquaculture. Increased production of fish feed, some of which is animal-based contributes to GHG emissions via livestock production. However, the contribution of aquaculture to climate change is deemed to be relatively small despite being significant when compared to other food production sectors. For example, the contribution of aquaculture to global GHGs, particularly CO_2 emissions in 2010 was estimated at ~7% of the agricultural sector's contribution that year [6]. But the pathways and contribution of aquaculture production to global GHGs emission is still poorly understood and requires further investigation. Furthermore, the production of plastics adds to the greenhouse gas emissions that drive climate change. For instance, in Europe, the production of plastic materials uses 4–6% of gas and oil consumption, and in 2014, 39.5 percent of post-consumer plastic waste was utilised for energy recovery [87]. Climate change is likely to impact human exposure to environmental contaminants from aquaculture foods; however, the extent of the change is yet to be quantified due to the assortment of pathways and mechanisms involved. To achieve sustainability in aquaculture, the issues of pollution (plastic and chemical) and climate change require attention.

Implications for food safety and the ecosystem

Climate change is considered a risk to global food production and a major threat to the quality and quantity of production [73]. Studies show that eating aquatic food can decrease the risk of heart attack, stroke, obesity, and hypertension due to the presence of low saturated fat and higher polyunsaturated fat, including omega-3 fatty acids [64]. However, aquatic foods may be contaminated with microplastics through ingestion of natural prey, adherence to the organism's surface, or during the processing and packaging phases. MPs ingestion is harmful to aquatic organisms as it can cause a false sense of satiety, gut blockage, and inflammation of tissues. A sustained decrease in feeding may result in diminished mobility, weight loss, impairment of growth and reproduction, or even the death of organisms [109]. As MPs aggregate in the digestive tract of organisms, smaller particles can enter and stay in the circulatory system [24]. Nearly 700 species of aquatic organisms are known to be impacted by MPs, and MPs have been detected at various trophic levels [9]. MPs will migrate through the food web in tandem with aquatic organism predation. Since humans are the ultimate consumers in the aquatic food web, the introduction of MPs into humans has been proven inevitable in several studies. Besides, MPs have been detected in human placenta, faeces, colon, lungs, sputum, liver, breastmilk, and blood [7, 51, 90, 114]. Furthermore, when an aquatic organism is consumed intact by humans, there is a higher chance of exposure than when the digestive tract is removed [18]. The knowledge of the effects of microplastics on humans is still very limited. However, animal studies indicate that their translocation to different organs occurs, leading to adverse effects. The key factors contributing to MPs toxicity are their physical and chemical properties, concentrations, and the presence of microbial biofilms [93].

Synthetic plastics are non-biodegradable, so they persist for a long time in the environment. Microplastics can leach toxic chemicals into the environment. They attract and concentrate heavy metals and organic pollutants dissolved in the water, thereby introducing more layers of harm to organisms and the ecosystem. The association between plastics/MPs and chemical pollutants such as PCBs, OCPs, PAHs, and heavy metals has been established by several studies [31, 33, 65]. A study found that the abundance of plastic particles like PE and PVC in sediment could affect enzymatic activities, microbial diversity, and aquatic plant growth. Furthermore, physicochemical parameters such as total organic carbon (TOC), total nitrogen (TN), and pH decreased, potentially altering the diversity and stability of the aquatic ecosystem [61]. Another study reported that the concentration of microplastic in the sediment had a greater influence on the sediment's temperature than the colour of the microplastic [35]. Sediment with higher microplastic concentrations had greater increases in temperature relative to the control, with the black 30% v/v treatment having the highest mean difference in temperature at 0.58 °C. This increase could significantly alter sea turtle hatchling sex ratios, physiological performance, and embryonic mortality [35]. Microplastics contain additives such as phthalate esters, BPA, pigments, UV stabilisers and so on, that have toxic effects on microalgae and other organisms in water [30, 32, 42]. In a recent study, high-throughput sequencing revealed the alpha diversities of bacterial and fungal communities were reduced by microplastics, and bacterial community structures were significantly altered under all microplastic treatments, with clustering for the same size class for polystyrene and polyethylene. Fungal community structures were also considerably affected for all MPs, with polystyrene (PS) and polyethylene (PE) exhibiting different effects [115]. These alterations in fungi and microbe communities are indicative of the ability of microplastics to perturb microbial-involved carbon and nitrogen cycling in the ecosystem. These findings imply that the presence of MPs and chemical pollutants may alter the ecological balance of the aquaculture ecosystem and impact its sustainable production if not monitored and controlled.

Mitigation strategies and recommendations

Based on the foregoing, the following mitigation strategies are recommended:

(1) Many coastal pond systems are found in developing countries, where there may be little awareness about the impacts of lost plastics and the need to ensure they are stored and disposed of responsibly, along with a lack of infrastructure for plastic collection and recycling. Making the local community aware of these impacts will guide their actions and choices.

(2) Microplastics monitoring and remote sensing technology are proactive measures against MP contamination [111]. The majority of aquaculture farms only monitor their gear after severe storms, not on a regular basis, and there are currently no standards or standardised processes in place for these farms to monitor gear loss [97]. Standards and regulations guiding the quality and durability of the materials used in aquaculture should be put in place. The standards contribute greatly to reduction in the lost gears and equipment at sea. As an example, Scotland has set standard guiding Finfish aquaculture that specifies the specific standard of gears and equipment [44].
(3) Controlling the use of chemicals and plastic fishing gears in aquaculture and increasing the recovery rate of the fishing gears, reducing or replacing the use of plastic packaging if aquaculture is to stem its contribution to the global plastics problem.
(4) Climate change mitigation and adaptation measures to build resilience in fisheries and aquaculture systems must be implemented in a multi-dimensional and multi-sectoral manner across all regions.
(5) Practice of sustainable and responsible aquaculture. Since our oceans and waterways are interconnected, any actions in one location affect the ecology in another. Practitioners must engage in responsible, sustainable aquaculture if we are to guarantee the continuous farming of these habitats for food.

Areas for future research

(1) Studies have indicated that the contribution of aquaculture to global plastic pollution is underestimated. An appropriate estimation will aid monitoring and abatement efforts. Most of the available current studies are from Asia, especially China. It is important to have more studies from other regions around the world including Africa, Europe, the Americas and Australia.
(2) During the literature search for this review no studies indicating aerial deposition of MPs in aquaculture were found. The contribution of aerial deposition could also provide further information on estimation and impacts of MPs to the aquaculture ecosystem.
(3) The pathways and contribution of aquaculture production to global GHGs emission and climate change is yet to be adequately elucidated and measured and requires further investigation.
(4) Chemical pollution in aquaculture needs further investigation to provide a robust model for accurate assessment of risks and impact of consuming contaminated species.
(5) More studies are required to clearly explain and quantify the role of climate change in aquaculture food contamination.

Conclusion

The nexus between plastic pollution, persistent toxic chemicals, and climate change in the aquaculture ecosystem is elucidated in this review. While the impacts of this tripod link may not be immediately obvious (largely due to underestimation and underinvestigation), it is important to know that they exist and are capable of presenting more severe layers of potential exposure and threats to aquaculture organisms and the ecosystem. The aquaculture industry is still growing rapidly; therefore, the problems highlighted cannot be overlooked since the sector is a vital avenue for meeting global food security goals. However, the safety of aquaculture products, which is pivotal to the well-being of consumers, is threatened by the effects of climate change and its impact in driving chemical and plastic contamination. Hence, appropriate steps must be taken to ensure that aquaculture is not unduly exposed to environmental contaminants like microplastics, toxic chemical pollutants, and climate change effects.

Abbreviations

AMAP	Arctic Monitoring and Assessment Programme
ARGs	Antibiotic resistance genes
As	Arsenic
BPA	Bisphenol A
Cd	Cadmium
CFCs	Chlorofluorocarbons
COVID-19	Coronavirus disease
CPM	Chlorpyrifos methyl
Cr	Chromium
Cu	Copper
DDTs	Dichlorodiphenyltrichloroethane
DO	Dissolved oxygen
EIT	European Institute of Innovation and Technology
EPS	Expanded polystyrene
FAO	Food and Agriculture Organisation
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHGs	Greenhouse gases
Hg	Mercury
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
Mn	Manganese
MNPs	Micro(nano)plastics
MPs	Microplastics
Ni	Nickel
NOAA	National Oceanic and Atmospheric Administration
NTP	National Toxicology Programme
OCPs	Organochlorine pesticides
PAHs	Polycyclic aromatic hydrocarbons
Pb	Lead
PCBs	Polychlorinated biphenyls
PE	Polyethylene
PFAS	Perfluoroalkyl and polyfluoroalkyl substances
POPs	Persistent organic pollutants

PVC	Polyvinyl chloride
SDGs	Sustainable Development Goals
TN	Total nitrogen
TOC	Total organic carbon
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
Zn	Zinc

Author contributions

O.H.F. conceptualised, curated data, and wrote the original draft of the manuscript; F.A. participated in data curation, preparation of figures and graphics; A.A. and I.A.O. were major contributors in writing the manuscript; O.O. edited and reviewed the manuscript; and N.B. was involved in the conceptualisation, review, editing, and supervision of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Competing interests

Omowunmi Fred-Ahmadu (the Corresponding Author) is a Guest Editor in this Special Issue.

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