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Review

An assessment of approaches and techniques for estimating water pollution releases from aquaculture production facilities

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ABSTRACT

The rapid expansion of the aquaculture industry raises concerns about water pollution from aquaculture production facilities (APFs). APFs release pollutants, including fish feed and feces, threatening the environment. The United Nations has introduced regulatory tools like the National Baseline Budget of pollutants (NBB) and Pollutant Release and Transfer Registers (PRTRs) to monitor pollution. However, these tools lack specific capabilities for estimating aquaculture-related pollution, especially from mariculture non-point sources (NPS). The United Nations Programme for the Assessment and Control of Marine Pollution in the Mediterranean (UNEP/MAP) stresses the need for an inventory and guidance document. Our comprehensive literature review focused on (1) NPS discharges of specific pollutants from APFs, (2) methods for estimating potential pollution releases from aquaculture, and (3) compiling information into a guidance document summarizing estimation methods. The geographical coverage of our study includes Europe, Australia, the USA, Canada, and East/Southeast Asia.

1. Introduction

Over the last five decades, aquaculture, which involves cultivating aquatic organisms, has witnessed remarkable growth on a global scale (FAO, 2004; Martinez-Porchas and Martinez-Cordova, 2012; Bhavsar et al., 2016). Fig. 1 displays the species composition, production, and growth trends in aquaculture during the 20-year period from 1997 to 2017. The Food and Agriculture Organization (FAO) of the United Nations' Fisheries and Aquaculture Division has been regularly publishing biennial reports titled "The State of World Fisheries and Aquaculture" since 1995. These reports provide in-depth technical insights, comprehensive analyses, and extensive data on worldwide fisheries and aquaculture, covering both global and regional perspectives (FAO, 2004; FAO, 2020; FAO, 2022).

As per the 2020a report by FAO, global food fish consumption exhibited substantial growth over the past five decades (1961 to 2017) at an average annual rate of 3.1 %. This rate surpassed the annual world population growth (1.6 %) and the growth of all other animal protein foods, including meat, dairy, and milk (which increased by 2.1 % per year) (FAO, 2020a). In 2020, world aquaculture production reached a record high of 122.6 million tonnes (Mt), with 87.5 million tonnes attributed to aquatic animals worth USD 264.8 billion and 35.1 million tonnes of algae worth USD 16.5 billion. Of this production, approximately 54.4 million tonnes originated from inland waters, and 68.1 million tonnes came from marine and coastal aquaculture. Asia remained the dominant contributor to global aquaculture production, accounting for over 90 % of the total output (FAO, 2022). FAO predicts that aquaculture will continue to play a crucial role in driving global fish production, projecting a substantial increase to 106 million metric tonnes by 2030, representing a 32 % rise from the 2020 figures (World Economic Forum, 2023).

However, the rapid expansion of aquaculture production has led to significant marine and freshwater pollution, posing escalating risks to human health and the environment (Martinez-Porchas and Martinez-Cordova, 2012; Bhavsar et al., 2016; Ahmad et al., 2022; Yuan et al., 2023). As aquaculture is increasingly promoted as a pivotal means of sustainable food production and plays a vital role in ensuring food security (Little et al., 2016; FAO, 2020a, 2020b; Azra et al., 2021), there is an urgent need to comprehensively assess and quantify the pollution releases and discharges originating from aquaculture production facilities (APFs) on a global scale. Typically, chemical releases and transfers from industrial activities are quantified and annually reported in Pollutant Release and Transfer Registers (PRTRs). These PRTRs function as internationally recognized legal regulatory instruments and monitoring tools for the reporting of chemical releases and transfers stemming from diverse industrial operations (OECD, 1996; UNECE, 2008; OECD, 2023a; UNECE,

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2023). Generally, facility owners or operators responsible for releasing contaminants are obligated to measure their discharges and regularly submit reports to governmental authorities (OECD, 2018). This information is publicly accessible through a database that offers comprehensive information on the released chemicals, their respective locations, quantities, and the entities held accountable (OECD, 2023a).

Presently, over 50 countries have successfully established PRTRs or have initiated pilot programs, with increasing interest in their implementation observed across Asia, South America, and Africa (USEPA, 2023). Furthermore, as a complementary tool to PRTRs, the National Baseline Budget of Pollutants (NBB) was proposed and ratified by the UNEP/MAP Contracting Parties. The NBB is designed to monitor progress, on a five-year cycle, regarding measures taken to mitigate and prevent land-based pollution (UNEP MAP, 2019).

To date, various industries have developed techniques and methodologies for estimating pollutant releases into the air, water, and land (OECD, 2023b; OECD, 2023c). However, it's important to note that releases of non-point source (NPS) pollution into water from the aquaculture sector are not currently covered by either PRTRs or the NBB. Additionally, there is a lack of guidance documents providing information on how to assess or estimate this type of pollution discharge (OECD, 2021b; OECD, 2023a). Given the ongoing expansion of the aquaculture sector, the United Nations Programme for the Assessment and Control of Marine Pollution in the Mediterranean (UNEP/MEDPOL) has emphasized the urgent necessity of creating an inventory and a guidance document that encompasses techniques and methodologies for countries to use in estimating pollution arising from NPS related to aquaculture (Cavus, 2020).

In light of these concerns, this review aims to (i) conduct a comprehensive assessment of non-point pollution releases and discharges from APFs, (ii) review existing inventories, approaches, methods, and techniques used for estimating these releases, and (iii) compile and integrate information to create an inventory and a guidance document for estimating non-point source pollution releases from APFs.

2. APFs pollution sources and adverse effects on the environment

Aquaculture production involves the utilization of various resources, such as water, land, feed, fertilizer, energy, capital, and labor. It exerts significant impacts on ecosystems due to the release of nutrients, diverse chemical and microbial pollutants, the use of disinfectants and

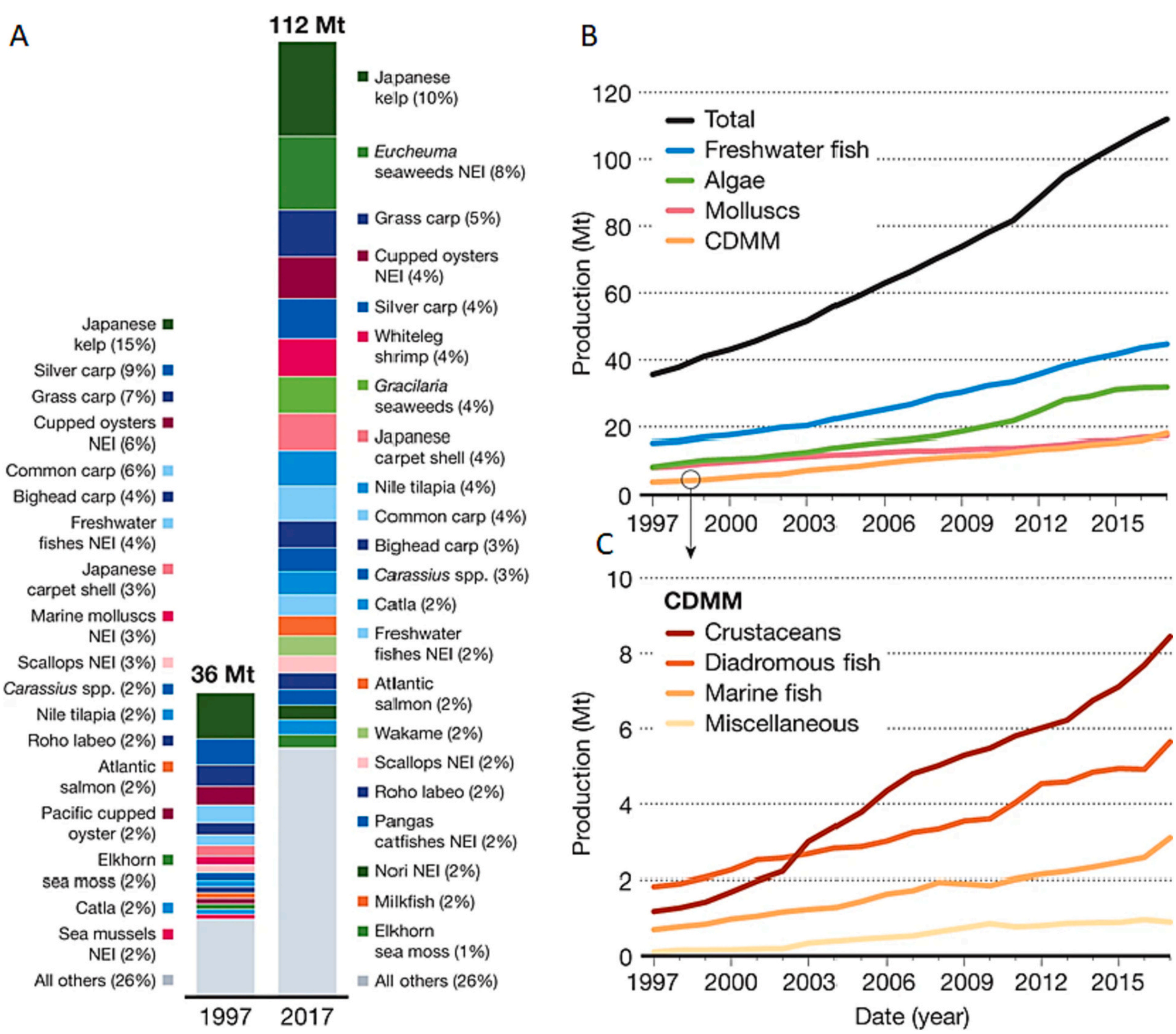

Fig. 1. The composition, production, and growth of global aquaculture were analyzed over a 20-year period from 1997 to 2017, as presented in the research by Naylor et al. (2021). The study categorized the species into three groups: (A) blue, freshwater fish, shellfish, diadromous fish, and plants and algae; (B) total, freshwater fish, algae, and molluscs; and (C) crustaceans, diadromous fish, marine fish, and miscellaneous species (CDMM). Reprinted with the permission of Naylor et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

veterinary antibiotics, and alterations to water dynamics, as well as the introduction of non-native species (Mente et al., 2006; Troell et al., 2014; Zhang et al., 2015; Ahmad et al., 2022). The adverse environmental effects of aquaculture production facilities (APFs) are influenced by several factors, including the type of aquaculture method, species being cultured, geographical location, and feeds and feeding practices (Funge-Smith and Phillips, 2001; Domínguez and Martín, 2004; Bhavsar et al., 2016; Kurniawan et al., 2021).

Regardless of the production method used, the main pathways through which contaminants are released from APFs include fish feed, the use of medications, disinfectants, antifoulants, and fish fecal matter (Martinez-Porchas and Martinez-Cordova, 2012; Bhavsar et al., 2016). Fig. 2 depicts APFs main pollution sources and their impacts on the environment. Fish feed, in particular, has been identified as a significant concern and the primary source of pollution (Tacon et al., 2012; Schalekamp et al., 2016; Dauda et al., 2019). The production of fishmeal and fish oil, derived from various sources such as whole fish (mainly small pelagic fish, Peruvian anchoveta, sardine, capelin, mackerel and herring), fish trimmings and bycatch, also contributes to waste production in aquaculture (Tacon and Metian, 2009; Troell et al., 2014; Schalekamp

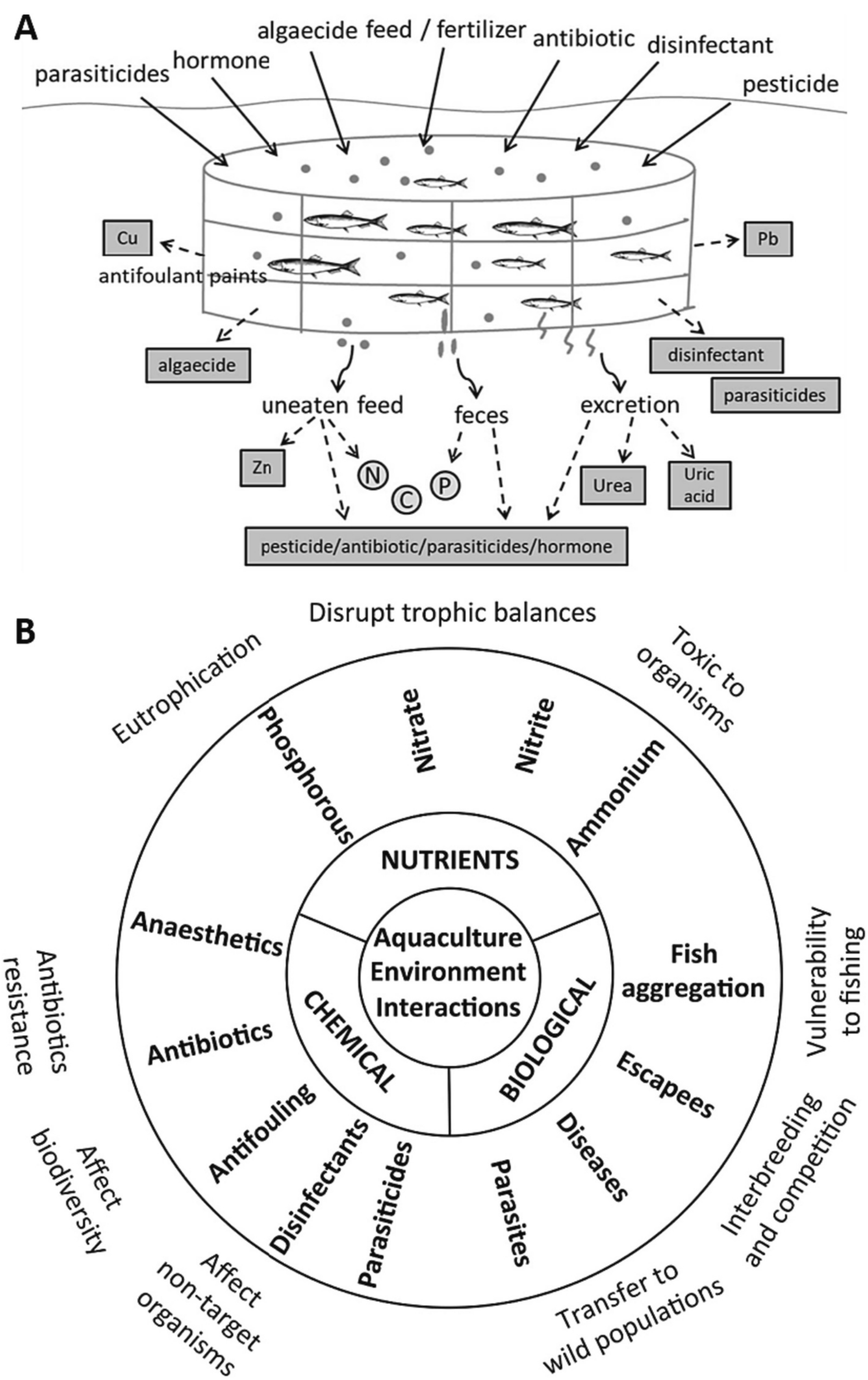

Fig. 2. (A) APFs Pollution Sources. Reprinted with permission from Wang et al. (2020). (B) Adverse Effects on the Environment. Reprinted with permission from Carballeira Brana et al. (2021).

et al., 2016; Boyd et al., 2022; FAO, 2022). The fishmeal and fish oil production industry heavily depend on the capture of specific species, notably anchoveta, which is significantly influenced by the El Niño-Southern Oscillation. However, with global climate change, increasing demand for fish-based diets, and the consequent depletion of essential raw materials like small pelagic fish and other species, there is a rising tendency to utilize by-products such as krill. Nevertheless, as highlighted in the 2022 FAO report, the processing of krill meal faces production challenges stemming from its fluoride content (FAO, 2022).

The waste generation from fish feed is influenced by factors like nutrient composition, production method, feed size relative to fish size, feeding amount, technique, and storage duration (Miller and Semmens, 2002; Schalekamp et al., 2016; FAO, 2022).

The accumulation of uneaten food and fish feces in the sediment beneath fish cages, affecting localized areas within approximately 20–50 m surrounding the cages has been reported (Mente et al., 2006; Quero et al., 2020; Go et al., 2023). In recent times, the substitution of marine ingredients with plant material like soybeans, maize, and rice has introduced terrestrial agriculture pesticides into APFs (Tacon and Metian, 2009; Troell et al., 2014; Zhang et al., 2014; Tacon and Metian, 2015; Olsvik et al., 2019). Vegetable oils with high omega-3 content and poultry oil are major alternatives to fish oil (Tacon et al., 2011).

Furthermore, non-nutritive feed additives, such as enzymes (e.g., proteases, amylases, phytase, and non-starch polysaccharide enzymes) and other substances (e.g., prebiotics, probiotics, phytogenic substances, immune-stimulants, and organic acids), are increasingly incorporated into aquatic feeds to enhance animal performance and health (Encarnação, 2015; FAO, 2022). The environmental consequences of APFs include changes in water quality, such as increased turbidity, altered pH (especially in freshwater systems), elevated nutrient concentrations leading to eutrophication and harmful algal blooms (HABs), and decreased dissolved oxygen levels (Domínguez and Martín, 2004; Olsen et al., 2008; Verdegem, 2013; Zhang et al., 2015). Nutrient enrichment, eutrophication and HABs have been recognized as the leading water quality impairment worldwide (Glibert and Burford, 2017; Drizo, 2019). Toxicity releases from APFs have also been reported as increasing concern (Jureša and Blanuša, 2003; Kelly et al., 2011; Nøstbakken et al., 2015; Karl et al., 2016; Guerranti et al., 2016; Vidal, 2017; Fernandez and Sanhueza, 2019).

According to Domínguez and Martín (2004), the release of cultured organisms or their reproductive cells into the wild can result in several consequences for wild populations. These impacts include cross-breeding, hybridization, depredation, competition, habitat destruction, and the potential spread of diseases. Shrimp farming, in particular, has been linked to notable destruction and depletion of mangrove forests in regions like East and Southeast Asia, Mexico, and Brazil (Yisheng et al., 2009; Bhavsar et al., 2016).

Inland and marine APFs are notably susceptible to the impacts of climate change, necessitating the implementation of adaptive measures to address extreme weather events. These events include floods, droughts, elevated temperatures, variations in rainfall patterns, sea-level rise, and saltwater intrusion (FAO, 2018a; FAO, 2022). The FAO technical report (2018a) offers a comprehensive resource on adaptation and mitigation options aimed at safeguarding freshwater and marine fisheries, as well as aquaculture production, from the adverse effects of these extreme events.

Furthermore, since 2018, the FAO has taken a leading role in developing the Progressive Management Pathway for Improving Aquaculture Biosecurity (PMP/AB). This pioneering initiative is dedicated to enhancing aquaculture biosecurity by improving health management and reducing antimicrobial resistance (AMR) within the aquaculture sector. Its overarching objective is to promote sustainable aquaculture production through the advocacy of sound husbandry practices, responsible environmental practices, and prudent antimicrobial use. These collective efforts contribute significantly to the global reduction of disease dissemination (FAO, 2020b; FAO, 2022).

2.1. Nutrients (total N and total P)

Nutrient release from Aquaculture Production Facilities (APFs) occurs through several main pathways, including unconsumed feed due to overfeeding, decomposition of dead organisms, excessive fertilization, and fecal matter (Bergero et al., 2001; Focardi et al., 2005; Martinez-Porchas and Martinez-Cordova, 2012; Bhavsar et al., 2016).

Inland feed-based aquaculture ponds, particularly those used for rainbow trout farming, are major contributors to nitrogen (N) release into the water. Approximately 60 to 80 % of N is released in the form of ammonia nitrogen (NH_3-N) due to uneaten feed, feces, and excretion by aquatic animals (Sidoruk and Cymes, 2018; Dauda et al., 2019). To prevent ammonium toxicity, large amounts of water (around 86,000 m3/ton of trout produced) are required, resulting in significant ammonium discharges into water bodies (Naylor et al., 2003).

Coastal and marine aquaculture, specifically shrimp farming, also contributes substantially to nutrient enrichment. Global annual shrimp production of approximately 5 million tons leads to discharges of 5.5 million tons of organic matter, 360,000 tons of N, and 125,000 tons of phosphorous (P) into the environment (Martinez-Porchas and Martinez-Cordova, 2012). This has significant implications for the ecological balance and water quality in coastal and marine ecosystems (Martinez-Porchas and Martinez-Cordova, 2012).

Intensive finfish and crustacean mariculture are responsible for releasing dissolved and particulate nutrients, causing nutrient loads in coastal areas to escalate. Projections indicate that nutrient inputs from mariculture may increase up to six-fold by 2050, exceeding the assimilative capacity in regions experiencing rapid mariculture growth (Bouwman et al., 2013). This could promote harmful algal blooms (HABs) by directly encouraging their growth or stimulating algae that HABs may feed on. Effective management strategies are necessary to address the potential environmental impacts associated with the expansion of mariculture activities (Bouwman et al., 2013).

2.2. Metals (copper, zinc, mercury and cadmium)

Copper (Cu) and Zinc (Zn) and their compounds can find their way into the marine environment through various routes. These pathways include uneaten food and food additives (Dean et al., 2007; Grigorakis and Rigos, 2011; Nikolaou et al., 2014; Tornero and Hank, 2016), fecal waste from farmed fish (Simpson et al., 2013; Tornero and Hank, 2016), and leaching from biocidal coatings used on submerged structures and net-cages in APFs (Clement et al., 2010; Simpson et al., 2013).

The application of anti-fouling paints using impregnation techniques is necessary to prevent fouling caused by shellfish, algae, crustaceans, and hydroids, and to protect nets from damage due to UV radiation (Bellona, 2009). However, these anti-fouling paints, predominantly containing copper oxide (CuO), Zinc pyrithione (ZnPT), and Zineb, contribute to elevated Cu and Zn levels in sediments near fish farms (Dean et al., 2007; Clement et al., 2010; Guardiola et al., 2012; Simpson et al., 2013; Tornero and Hank, 2016). For instance, in Norway, approximately 1 g of Cu is discharged for every 2 kg of farmed salmon produced, with about 160 tons of Cu leaching from fish farm nets into the sea annually (Bellona, 2009).

Research has revealed that 19 out of 25 anti-foulant products permitted for use in Scottish aquaculture contain Cu as the primary active ingredient, with some also containing Zn (Dean et al., 2007). Zinc pyrithione (ZnPT), a common anti-fouling agent, can undergo transchelation, leading to the release of zinc ions within the complex. These released Zn ions can interact with other free metal ions in seawater, forming various metal pyrithiones (Soon et al., 2019). The occurrence and extent of these chemicals and heavy metals in the environment are influenced by specific conditions and locations of aquaculture farms (Soon et al., 2019).

The widespread use of anti-fouling biocides in aquaculture raises concerns about potential metal accumulation in cultured fish. These biocides pose two types of risks: (i) ingestion of fish and shellfish by predators and humans and (ii) the development of antibiotic resistance in bacteria (Guardiola et al., 2012). Consuming contaminated fish and shellfish can have both lethal and sub-lethal effects, posing significant risks to human health and the immune defense mechanisms of exposed fish (Guardiola et al., 2012; Nikolaou et al., 2014; Soon et al., 2019).

Mercury (Hg) pollution in aquaculture poses a significant environmental concern due to its high toxicity, persistence in the environment, and health risks for both aquatic organisms and humans who consume seafood products. Numerous studies have explored Hg biogeochemical cycling in aquatic systems, the presence and bioaccumulation of Hg in seafood, as well as the associated risks of Hg exposure from fish consumption (Jureša and Blanuša, 2003; Botaro et al., 2012; Driscoll et al., 2013; UNEP, 2013; Gribble et al., 2016). However, research focused on understanding Hg sources, pathways, and transfers in Aquaculture Production Facilities (APFs) has been lacking (Karimi et al., 2012; Oliveira et al., 2015; Al-Sulaiti et al., 2022).

Hg enters aquatic environments through various natural and anthropogenic sources, including industrial emissions, atmospheric deposition, and runoff from the land. Once in the water, Hg can transform into methylmercury (MeHg), a highly toxic organometallic cation that accumulates in aquatic organisms (Hammerschmidt and Fitzgerald, 2006; Oliveira et al., 2015; Chen et al., 2021). Given its ability to magnify up the aquatic food chain, Hg can raise concerns in freshwater and coastal APFs, especially when they are supplied with contaminated feed or situated in areas with elevated mercury levels. Botaro et al. (2012) and Oliveira et al. (2015) examined Hg levels in the aquafeed of farmed tilapia in Brazil and found low concentrations (ranging from 5.2 to 33.2 μg kg^{-1} and 1.4 to 31.1 ng g^{-1}, respectively), well below the 100 μg kg^{-1} limit set by the European Commission. Additionally, Oliveira et al. (2015) estimated that the annual Hg input from fish farming to the Castanhão Reservoir amounted to less than 1.0 % of the total anthropogenic Hg input. In the United States, Karimi et al. (2012) investigated Hg patterns, distribution, and variability in commonly consumed seafood. Their study revealed that farmed fish generally exhibited lower average total Hg concentrations compared to their wild counterparts, with wild seafood containing 2 to 12-fold higher concentrations (Karimi et al., 2012).

Cadmium (Cd) is widely recognized as one of the most toxic and mobile elements in the environment, posing significant risks to both ecosystems and human health (Kubier et al., 2019; WHO, 2019). According to the World Health Organization (WHO), Cd can enter the environment through natural processes such as volcanic activity, rock weathering, and erosion, as well as various human activities including industrial processes, mining, and the improper disposal of Cd-containing products such as batteries and electronic waste (WHO, 2019). Additionally, the extensive use of phosphate fertilizers in agriculture contributes to Cd contamination in soil, which can then find its way into food crops, potentially exposing humans to this toxic element.

Once released, Cd has the capability to accumulate in soil and water, subsequently entering the food chain. This can disrupt vital biological processes, leading to a range of adverse effects, including organ damage, developmental abnormalities in wildlife, and an increased risk of cancer in humans (WHO, 2011; Hajeb et al., 2014; Kubier et al., 2019). Unlike mercury (Hg), which enters the human diet primarily through aquatic pathways, Cd predominantly enters the human diet through terrestrial sources, such as plants and vegetables. The bioaccumulation of soil Cd in rice grains is of particular concern in rice-fish coculture systems (RFS). These traditional agricultural systems have a history dating back thousands of years and are cultivated in rice-growing regions across six continents in 28 countries (Xie et al., 2011; Luo et al., 2020).

In areas located away from coastal regions and rivers, which are unaffected by industrial and agricultural pollution, the primary source of Cd in APFs is typically feed, as noted by Ayyat et al. (2017), Adamse et al. (2017), and Bernard and Adetola (2023). Another potential source of Cd contamination can be antifouling paint and fiber manufacturing, as highlighted by García-Bueno and Marín (2021). However, it is s worth noting that there has been relatively limited research on the Cd content in aquafeed. Tithi et al. (2020) investigated the risks of heavy metal contamination through commercial fish feeds in Bangladesh. Their findings indicated that Cd concentrations ranged from 0.012 to 0.027 mg kg^{-1}, which fell below the acceptable limit of 2 mg kg^{-1} established by the European Commission (EC, 2003). Similarly, Adeniji and Okedeyi (2017) and Bernard and Adetola (2023) carried out assessments of heavy metal concentrations in selected fish feed ingredients in Nigeria. Their studies revealed that Cd concentrations were also below the 2 mg kg^{-1} limit set by the European Commission (EC, 2003).

To mitigate and prevent heavy metal contamination in fish feed ingredients, Adeniji and Okedeyi (2017) proposed two measures. The first measure involves regular monitoring and assessment of heavy metal contents in fish feed ingredients by designated authorities at the local government, state, and national levels. The second measure entails conducting regular training programs for farmers and small-scale oilseed cake producers to educate them on the proper storage and handling of fish feed ingredients. These steps can contribute to minimizing Cd contamination in aquafeed and subsequently reduce the risk of Cd entering the aquaculture system.

2.3. *Total organic carbon*

The primary mechanisms for organic matter transfer through seawater encompass the dissolution of fecal pellets, excess feeding, cellular breakdown, and bacterial activity (Sowles et al., 1994; Mostofa et al., 2013; Mahmood et al., 2017). In properly managed fish farms, approximately 30 % of the applied feed is estimated to become solid waste, leading to the deposition of organic matter in the sediments beneath fish cages (Miller and Semmens, 2002). This accumulation of sedimentary organic matter negatively impacts benthic communities by reducing oxygen levels and generating methane and hydrogen sulfide (Go et al., 2023).

The effects of aquaculture on the distribution of dissolved organic matter in the marine environment have been extensively studied (Sowles et al., 1994; Mostofa et al., 2013; Mahmood et al., 2017; Sui et al., 2019; Kim et al., 2022). Research from Iceland indicated a significant increase (4 to 27-fold) in the sedimentation of organic carbon (OC) beneath fish farms compared to control sites, which decreased rapidly with distance from the farm (Norði et al., 2011). The incorporation of lower trophic-level species, such as shellfish and seaweed, alongside fish or shrimp monoculture in coastal waters, has the potential to assimilate organic matter from the surrounding water. This assimilated organic matter is subsequently released through excretion, becoming a significant component of the organic pool within the ecosystem (Mostofa et al., 2013).

The contribution of primary production to carbon loading in fed aquaculture systems, including cages, is estimated to be higher than the amount of carbon directly fed to the aquaculture organisms (Verdegem, 2013). A more detailed mass balance, incorporating different feed components such as dry organic matter (DOM), chemical oxygen demand (COD), C, N, and P, has been proposed.

A benthic-pelagic model investigated by Yakushev et al. (2020) demonstrated the biogeochemical impacts of fish farms, extending up to 1 km from the farm site. These impacts included increased levels of organic matter in sediments, oxygen depletion in both bottom water and sediments, denitrification, reduction of metals and sulfur, as well as changes in oxygen, ammonium, phosphate, and organic matter levels in the surface water near the fish farm. These findings underscore the potential influence of Aquaculture Production Facilities on the surrounding marine environment, affecting both seafloor and surface water chemistry.

2.4. Pesticides

The main sources of pesticides in aquaculture production, especially in salmon farming, are fish feed and parasite control. Studies conducted by Kelly et al. (2011), Zhang et al. (2014), Nøstbakken et al. (2015), Vidal (2017), Fernandez and Sanhueza (2019) have highlighted this concern. The practice of supplementing fish feed with plant-based agricultural products and by-products poses a potential risk of pesticide transfer from plants to fish. This may lead to the accumulation of pesticides in the liver, fat, and tissues of fish, as observed in research by Pucher et al. (2014) and Schlechtriem et al. (2016). Research carried out by Cheung et al. (2007) revealed significantly high concentrations of organochlorine pesticides (OCPs) in fish collected from fishponds in the Pearl River Delta region of Asia. Similarly, studies investigating the presence of OCPs in human tissues, such as milk and plasma, in both Hong Kong and Guangzhou populations, showed a significant correlation with the frequency of fish consumption (Wang et al., 2013; Zhang et al., 2014).

Unyimadu et al. (2018) examined ten different brackish water fish species in Nigeria's river Niger and found that all investigated species exceeded the World Health Organization (WHO)/FAO guideline value of 2000 μg kg^{-1} fresh weight for OCPs. This raised concerns about potential harmful effects on human health. The screening of Atlantic salmon feeds in Europe revealed the presence of chlorpyrifos-methyl (CPM) and Chlorpyrifos (CPF), which are highly toxic organophosphorus pesticides commonly used in agriculture (Portoles et al., 2017; Olsvik et al., 2019). In the Mediterranean Sea, residues of pesticides like Metribuzin DADK, propamocarb HCl, and piperonyl butoxide (PBO) were detected in muscles of various marine fish species and seaweeds in Iskenderun Bay, Turkey (Polat et al., 2018).

Storelli et al. (2009) discovered elevated levels of polychlorinated biphenyls (PCBs) and OCPs in the livers of two deep-sea fish species, roughsnout grenadier, and hollowsnout grenadier, in the Adriatic Sea. Similarly, PCBs and OCPs were found in the sediments and Siganus rivulatus (marble spinfoot) from different areas along the Egyptian Mediterranean Coast (Sheradah et al., 2018), Greece (Kasiotis, 2009), Spain (Serrano et al., 2008), Italy (Masci et al., 2013), and France (Lazartigues et al., 2013). Ibrahim et al. (2013) conducted a study on freshwater fish species native to Europe and identified 27 species at an elevated risk of pesticide exposure.

2.5. Persistent organic pollutants (POPs)

The main source of persistent organic pollutants (POPs) in farmed fish, especially farmed Atlantic salmon, is fish oils derived from pelagic fish species used in fish feed production. These POPs can accumulate in fish tissues, posing potential risks to human health (Petrenya et al., 2011; Solé et al., 2013; Barni et al., 2016). Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), commonly known as dioxins, are highly lipophilic and tend to accumulate in fatty tissues of both humans and animals, including the livers of fatty fish (Karl et al., 2016). Studies have shown that the levels of organic contaminants in cod livers vary depending on the fishing area (Karl and Lahrssen-Wiederholt, 2009; Julshamn et al., 2013; Karl et al., 2016).

The primary cause of Polycyclic aromatic hydrocarbons (PAH) pollution in aquatic environments is oil spill accidents (Ladwani et al., 2013; Koyama et al., 2016; Pulster et al., 2020; Honda and Suzuki, 2020). These PAHs are major components of crude oil and fall into different categories such as PAHs, aliphatic saturated hydrocarbons, aliphatic unsaturated hydrocarbons, and alicyclic saturated hydrocarbons (Ladwani et al., 2013; Koyama et al., 2016; Pulster et al., 2020; Honda and Suzuki, 2020). The presence of these four categories of PAHs in ecosystems and their potential impact on human health is a major concern due to their carcinogenic properties (Rengarajan et al., 2015; Ferrante et al., 2018; Honda and Suzuki, 2020; Patel et al., 2020).

2.6. Microplastics

Microplastics (MPs) are plastic particles that have a size of less than 5 mm in their longest dimension, and nanoplastics are even smaller particles, measuring less than 100 nm (Barnes et al., 2009).

These plastic particles can find their way into aquatic environments through various pathways and have become a global concern, prevalent in freshwater, marine, benthic, terrestrial environments, as well as in the atmosphere, as documented by Stothra Bhashyam et al. (2021), Kurniawan et al. (2021a), Kurniawan et al. (2021b), Walkinshaw et al. (2022), and Wu et al. (2023). In APFs, the two primary sources of MPs are the external environment (including rivers, land, coastal areas, and marine environments) and the aquaculture production processes, encompassing aspects like feed, packaging of aquaculture products, and fishing gears. This information is supported by the research of Lin et al. (2022), Walkinshaw et al. (2022), and Wu et al. (2023). Fig. 3 illustrates the sources and movement of MPs originating from APFs.

Wu et al. (2023) conducted a comprehensive review of MPs pollution in aquaculture, highlighting a significant concern regarding the contamination of wild-caught fish and shrimp, essential ingredients in aquaculture feed, with MPs. They presented data from various studies examining the presence of MPs in fish meals. For instance, one study discovered MPs in fish meals derived from salmon, sardine, and kilka collected from the Persian Gulf and Caspian Sea in Southern Iran, with MPs' levels comparable to those found in cultured carp (Hanachi et al., 2019). Research conducted by Castelvetro et al. (2021) revealed the presence of 50–100 mg kg^{-1} of polystyrene and highly oxidized polyolefins, along with 12.9 mg kg^{-1} of polyester in Italian fish meals (Wu et al., 2023). Yao et al. (2021) collected fish meal samples from five different countries (China, Peru, Denmark, Russia, and Thailand) and detected 10.7 microplastics/100 g and 5.4 microplastics/100 g of MPs in shrimp and fish meals, respectively. They observed a variety of MP colors, including black, red, and the rarely reported orange. The predominant chemical components identified were olefins, polyester, paraffin, and polyethylene. In a study by Walkinshaw et al. (2022), commercially-sourced aquaculture feedstocks, including fish meals and soybean meal, were investigated as potential sources of contamination for farmed fish in the UK. Their research identified anthropogenic particles, including MPs and semi-synthetic cellulosic fibers, in both fishmeal and soybean meal, with concentrations ranging from 1070 to 2000 particles kg^{-1}. They suggested that farmed Atlantic salmon could potentially be exposed to a minimum of 1788–3013 anthropogenic particles from aquaculture feed throughout their commercial lifespan.

MPs can contain a mixture of chemicals and additives from manufacturing processes. Furthermore, they have the ability to efficiently adsorb or absorb persistent, bioaccumulative, and toxic contaminants (PBTs) from the surrounding environment (Collignon et al., 2012; Wang et al., 2016; Lusher et al., 2017; Güven et al., 2017; Zhang et al., 2017; Galgani et al., 2019; Honda and Suzuki, 2020; Galgani et al., 2021). As a result of their wide distribution in both freshwater and marine environments and their potential to accumulate harmful contaminants, MPs have become a significant environmental concern for aquatic ecosystems (Lusher et al., 2017; Güven et al., 2017; Zhang et al., 2017; Honda and Suzuki, 2020; Kurniawan et al., 2021a; Kurniawan et al., 2021b; Galgani et al., 2021). To effectively address and mitigate the impact of MPs on aquatic ecosystems, it is essential to understand their pathways of entry and distribution in various environmental components.

Galgani et al. (2019) proposed that inert polystyrene MPs perform a function akin to that of inorganic ballasting particles, stimulating heightened metabolism and fostering interactions among autotrophic (Synechococcus) and heterotrophic bacteria. This, in turn, leads to an increased production of dissolved organic matter (DOM) polymers and the precursors of transparent exopolymer particles (TEP), ultimately resulting in enhanced aggregation into gel-like macromolecules. The authors put forth the hypothesis that MPs, acting as growth substrates

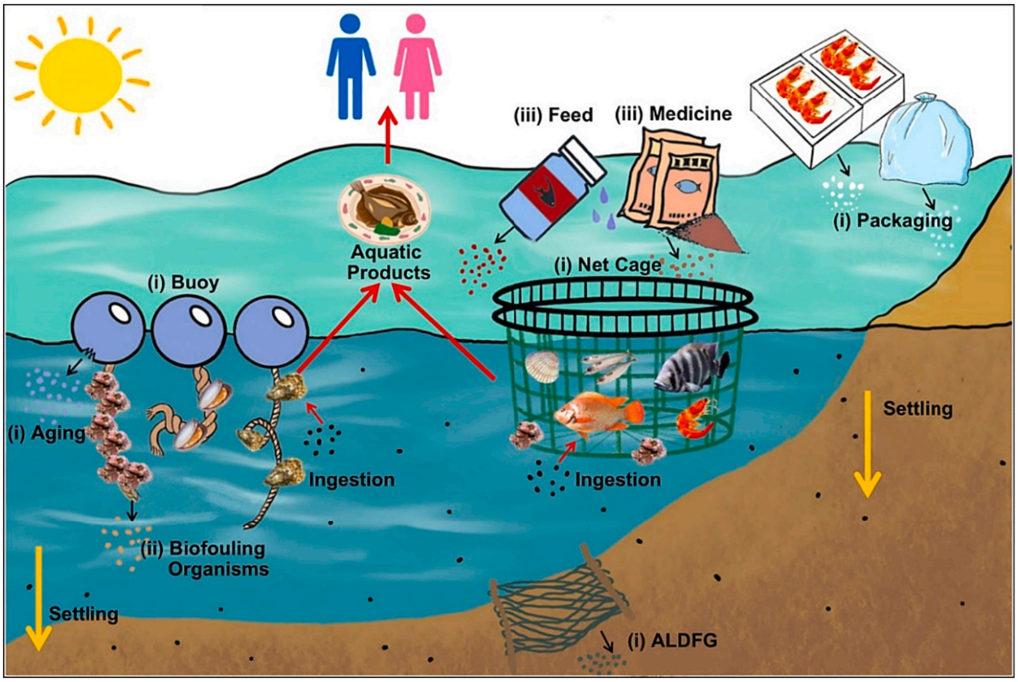

Fig. 3. The main sources and pathways of MPs release from APFs. Reprinted with permission from Lin et al. (2022).

for marine plankton, may augment the biological production of DOM and its subsequent aggregation into marine gel particles that envelop suspended particulates. These aggregates, enriched in organic matter, become easily ingestible by zooplankton, ultimately passing through fish excretion. Consequently, this aggregation process could play a pivotal role in facilitating the transport of MPs throughout the water column and their subsequent accumulation in the deep ocean (Galgani et al., 2019).

3. Overview of guidelines

The FAO established the Code of Conduct for responsible fisheries nearly three decades ago, providing a global framework that delineates principles and international standards for guiding responsible practices. Its primary objective is to ensure the effective conservation, management, and sustainable development of living aquatic resources, with a strong emphasis on protecting ecosystems and biodiversity (FAO, 1995). Regarding aquaculture, the Code's general principles encourage nations to consider aquaculture as a means to promote income diversification and dietary variety. It also underscores the importance of responsible resource utilization and the minimization of adverse impacts on the environment and local communities (FAO, 1995).

Article 9 of the Code elaborates on the rules for the development of aquaculture, including culture-based fisheries. This article consists of four subsections: development of aquaculture in areas under national jurisdiction (9.1), development of aquaculture within transboundary aquatic ecosystems (9.2), use of aquatic genetic resources for aquaculture (9.3), and responsible aquaculture at the production level (9.4). In particular, section 9.1.5 underscores the importance of countries establishing specific procedures for aquaculture, conducting appropriate environmental assessments, and monitoring activities to minimize adverse ecological changes. Sections 9.4.3 to 9.4.7 summarize critical regulations pertaining to APFs. These sections emphasize the need for countries to promote the use of suitable feeds, feed additives, and fertilizers (9.4.3), employ effective farm and fish health management practices while minimizing the use of therapeutants, hormones, drugs, antibiotics, and other disease control chemicals (9.4.4), regulate the use of chemical inputs that pose hazards to human health and the environment (9.4.5), properly manage waste disposal, including sludge, dead or diseased fish, excess veterinary drugs, and others (9.4.6), and ensure the food safety and product quality of aquaculture products (FAO, 1995).

However, it is important to note that the Code does not provide specific guidelines or procedures for estimating potential contaminant releases and discharges from APFs. These estimates are essential to ensure the fulfillment of the recommendations for responsible aquaculture development. Moreover, 30 years since the establishment of the Code, there is still a lack of comprehensive inventories and guidelines that provide methodologies and techniques for estimating both point and nonpoint releases and pollutant loading from aquaculture production activities. This scarcity can be attributed to the complexity of data and information that would need to be collected and reported, as well as diverse nature of regulations and international oversight governing the aquaculture industry. To estimate pollutants release and loading from APFs, farm managers and operators would need to provide information detailing aquafeed ingredients, feeding strategy, species being farmed, the production system in use, and the specific location of the farm. However, multiple agencies are involved in overseeing different aspects of aquaculture practices, leading to challenges in developing unified guidelines. These regulations cover various areas, including site selection, feed supply and strategy, water quality management, food safety (FAO, 2020; OECD, 2021a; FAO, 2022; FAO, 2023). In many cases, guidelines may not exist, may vary from country to country and even between states and territories within the same country (Siemers, 2009; Cole et al., 2009; Miao and Yuan, 2021; FAO, 2022). For example, in 2013 the FAO established Aquaculture Feed and Fertilizer Resources Information System (AFFRIS) with the aim to provide and disseminate the global information on aquaculture feed, feed ingredients and nutrient profiles of globally important selected aquaculture species (FAO, 2023). The website provides information on proximate composition of over 30 different feed ingredients. However, Feed and Feed Ingredient Standards have only been shown for Europe, China, India, Vietnam, Bangladesh and Thailand (FAO, 2023).

The geographical coverage of our study includes Europe, Australia, the USA, Canada and East and Southeast Asia (China, Indonesia, India and Vietnam). Our search for inventories and guidelines yielded only five documents, all of which were developed more than 20 years ago. With the steady growth of the aquaculture sector over the past few decades, there is an urgent and compelling need to update existing guidelines and develop standardized protocols for estimating NPS pollution releases and discharge loadings from APFs.

3.1. Europe

The primary guidelines for Fish Farming and Aquaculture were created by two organizations: the 'OSPAR Convention,' which oversees the Marine Environment of the North-East Atlantic, and the Helsinki Commission (HELCOM), responsible for protecting the Baltic Marine Environment.

The 'OSPAR Convention' originated in 1992 by amalgamating significant agreements from two prior conventions: the Oslo Convention (1972) concerning the Prevention of Marine Pollution from Waste Dumping by Ships and Aircraft, and the Paris Convention (1974) on the Prevention of Marine Pollution from Land-Based Sources. The OSPAR Commission was established as a successor to the Convention, tasked with administering it, developing policies, and forming international agreements.

In the year 2000, the OSPAR Commission formulated guidelines on Nutrient Discharges from Fish Farming within the OSPAR Convention Area. These guidelines presented two assessment methods: one based on the type of feed used, specific to the fish species being farmed, and the other based on the production type, estimating the non-converted nutrient discharges per ton of fish produced. Information gathered from various producers revealed that using dry feed with a DOM content exceeding 90 % results in approximately 40 to 70 kg of nitrogen (N) and 4 to 11 kg of phosphorus (P) per ton of fish produced remaining unconverted.

Moreover, the guidelines suggested calculating nutrient discharges separately for different aquaculture types, including marine and brackish-water net cage farming, intensive farming in ponds, basins, and channels, and extensive carp pond farming. However, specific data for this differentiation were not provided in the OSPAR guidelines.

HELCOM, established in 1974 as a regional platform for environmental policy-making, aims to protect the Baltic Sea marine environment from all sources of pollution. In 2006, HELCOM developed Guidelines for the compilation of waterborne pollution loads to the Baltic Sea (HELCOM, 2006). Section 3.1.3.3. (p.36) of these guidelines outlined methods for compiling annual pollutant loads for fish farming plants, with or without sludge treatment. The first approach required information on production parameters and feed consumption at the catchment level to quantify pollutant loading using mass balance equations, while the second approach was based on field water quality monitoring.

3.2. Australia

The Australian Government Department of Environment has developed two Emissions Estimation Technique Manuals aimed at assisting State and Territory authorities in estimating emissions of specified substances for the National Pollution Inventory (Environment Australia, 2000).

The first manual focuses on procedures and methods for estimating emissions solely from species cultivated in Tropical Aquaculture Facilities. The species covered include barramundi (lates calcarifer) and other fin fish, prawns (penaeus spp.), pearl oysters (pinctada spp.), red claw (cherax quadricarinatus), donkeys ear abalone (haliotis asinina), and crocodiles (crocodylus porosis; crocodylus johnstoni). Additionally, the manual provides an overview of the aquaculture industry in tropical Australia, which requires updating to reflect the present time.

The second manual provides guidelines for estimating emissions of Category 3 National Pollutant Inventory (NPI) listed substances, specifically nutrients discharged from temperate water finfish aquaculture commonly practiced in southern Australia (Environment Australia, 2001). The covered species include Atlantic salmon (salmo salar), trout (oncorhynchus mykiss and salmo trutta), tuna (thunnus maccoyii), silver perch (bidyanus bidyanus), eel (anguilla australis), barramundi (lates calcarifer), seahorse (hippocampus abdominalis), ornamental fish, and other native fish. If the annual emission estimates of nitrogen (N) and phosphorus (P) exceed 15 and 3 t, respectively, they must be reported to Environment Australia (EA) by the relevant State authorities.

3.3. USA

Approximately two decades ago, the U.S. Environmental Protection Agency (USEPA) introduced national regulations to control point source pollutant discharges from aquatic animal production facilities (AAPFs). This initiative was based on the results of an extensive survey that collected detailed technical and financial information from 3075 AAPFs respondents (Smith and Jordan, 2002; USEPA, 2002; USEPA, 2002b, 2002c).

The data obtained from the survey played a pivotal role in formulating the Effluent Limitations Guidelines and Standards for the Concentrated Aquatic Animal Production (CAAP) Industry Point Source Category (USEPA, 2002b). Additionally, it assisted in creating a facility-specific approach to estimate pollutant load reductions from CAAP Point Sources (USEPA, 2004).

Chapter 10 of the Guidelines provides a comprehensive description of this approach and the associated procedures. Section 10.3 (p. 308) specifically addresses the contribution of feeds to pollutant loads. This includes discussing feed constituents, feeding practices, feed conversion ratios (FCRs), the fate of feeds in AAPFs, and the method used to estimate raw pollutant loads. Furthermore, Section 10.7 (p. 329) presents a summary of estimates for loads of other pollutants, such as metals, PCBs, and veterinary drugs, that can be removed with solids (USEPA, 2004).

3.4. Canada

In Canada, the aquaculture industry is regulated by multiple levels of government. Provincial governments are the primary regulators and leasing authorities, with the exception of British Columbia and Prince Edward Island, where regulatory responsibility is shared with the federal government. The federal government's responsibilities include navigation regulations, disease prevention measures affecting international trade, and environmental protection under the Fisheries Act and the Health of Animals Act (Government of Canada, 2021).

The Aquaculture Activities Regulations Guidance Document provides comprehensive measures aimed at mitigating health and environmental impacts associated with aquaculture activities (Government of Canada, 2018). However, this document does not offer specific guidelines for estimating pollution loading from aquaculture activities.

Otu et al. (2017) discussed Ecosystems Impacts from P waste by freshwater cage aquaculture and suggested using bioenergetics models like Fish-PrFEQ (Cho and Bureau, 1998). This model can be used to estimate various factors related to aquaculture, including the amounts of feed used, the total phosphorus concentration of the feed, the digestibility of phosphorus in the feed, the phosphorus concentration of the fish, the feed conversion ratio, and the feed wastage caused by fish culture operations.

3.5. East and Southeast Asia

Asia is the world's leading aquaculture producer, contributing to 92 % of global production (Suzuki, 2021). China holds a dominant position in the region, accounting for nearly 58 % of the total output, followed by Indonesia (15.1 %), India (5.7 %) and Vietnam (3.6 %) (OECD, 2022; FAO, 2022; World Atlas, 2023). Each of these countries have developed comprehensive legislative frameworks for the regulations of aquaculture (FAO, 2018b; Wang and Liu, 2021; Intracolaw, 2021; FAO, 2023a; Skonhoft, 2023; Salvi, 2023; IMARC, 2023).

Currently, none of the existing regulations and policies address or provide guidelines or methodologies for estimating NPS pollutant discharges from APFs. However, some countries have developed regulations pertaining to aquafeed, with Vietnam notably having one of the most comprehensive approaches in this regard. In 2017, the Vietnamese government introduced Decree 39/2017/ND-CP, which focused on the state management of animal feed usage in livestock and aquaculture (World Trade Organisation, 2017). It included provisions related to aqua feed. However, when the Law on Fisheries came into effect on January 1, 2019, the regulations concerning aqua feed from this Decree were abolished. Nevertheless, today, all establishments involved in the production and trade of aqua feeds in Vietnam are required to adhere to four key requirements: (1) They must obtain a certificate of eligibility for aqua feed production. (2) They can only produce and trade products using ingredients approved by the Ministry of Agriculture and Rural Development. (3) They are obligated to provide product information that they produce or import to the National Fisheries Database. Aquatic feeds are only permitted to be circulated in the market after obtaining a receiving code on this system. (4) They must secure a declaration of conformity with the relevant national technical regulations for each type of aqua feed before these feeds are allowed to be circulated in the market (Intracolaw, 2021).

China's aquafeed industry is massive, with approximately 7000 aquafeed companies, making it significantly challenging to regulate (Newton et al., 2021). Moreover, a recent initiative by the Chinese government to shift away from using young or low-value fish in aquafeed production in favour of manufacturing compound feed (Fishsite, 2022) may further complicate efforts to gather information about the ingredients and their content in aquafeed products. In Indonesia, approximately 70 % of fishmeal is imported (NACA, 2017; FAO, 2023b).

To reduce dependence on imports, the Indonesian government launched the "self-sufficient fish feed" (GERPARI) program, which promotes fish feed production using agri-food wastes and by-products to support sustainable aquaculture (NACA, 2017; Prabakusuma et al., 2023). However, the sustainability of aquafeed produced from terrestrial sources raises concerns because these sources can potentially contaminate the feed with pesticides used in agriculture (Ibrahim et al., 2013; Portoles et al., 2017; Olsvik et al., 2019).

The Government of India has taken several initiatives, formulated policies, and issued guidance documents to encourage the sustainable growth of the aquaculture sector, as documented by Salvi (2023) and the National Fisheries Development Board (NFDB, 2023). Notably, the NFDB provides comprehensive guidelines for cage culture in both inland and marine open waters. In the state of Andhra Pradesh, specific measures have been put in place to regulate, supervise, manufacture, sell, and distribute fish feed. This is achieved through the Andhra Pradesh Fish Feed (Quality Control) Act of 2020 (Indiacode, 2020). However, similar to many other countries in the region, India currently lacks guidelines that provide methodologies and techniques for estimating NPS pollutant releases and discharge loadings from APFs.

In November 2019, the FAO and the Network of Aquaculture Centres of Asia-Pacific (NACA) collaborated to host a regional consultative workshop focused on evaluating aquaculture governance in the Asia-Pacific region. The outcomes of this workshop included a series of recommendations intended to improve the governance of the aquaculture sector and advance sustainable aquaculture production within the region, as detailed by Miao and Yuan (2021). However, it's important to note that these recommendations did not encompass the assessment of NPS pollution emissions from APFs.

In summary, the regions under review exhibit varying levels of regulation and guidelines for aquaculture activities. However, the comprehensiveness, coverage, and specific focus on estimating pollutant discharges differ significantly among these regions. A common gap observed across all regions is the absence of guidelines addressing NPS releases and discharges from APFs. This gap highlights a clear necessity for the development of more comprehensive and standardized guidelines that specifically target the estimation and management of NPS pollutant discharges from APFs on a global scale. Such guidelines would play a pivotal role in promoting sustainable and responsible practices within the aquaculture industry, while also ensuring the protection of aquatic ecosystems and public health.

4. Accuracy and uncertainty regarding current guidelines

When quantifying pollution from NPS, catchment models are commonly used, where emission factors are linked to known or easily obtainable source parameters (UNITAR, 1998; NSW EPA, 1999; OECD, 2021a, 2021b). These emission factors are applied to specific processes, and the estimated or calculated emissions from various sources are aggregated. However, estimating releases from NPS is challenging due to the wide range of sources involved (Novotny and Chesters, 1981; Drizo, 2019; Xue et al., 2022; Wang et al., 2022), leading to a higher risk of errors or uncertainty in pollution inventories (UNITAR, 1998; NSW EPA, 1999; OECD, 2021a, 2021b).

The OSPAR Guidelines (2000) highlighted several challenges in generating comprehensive and reliable datasets on nutrient discharges from aquatic animal production facilities (AAPFs). These challenges included incomplete or missing responses to questionnaires, lack of detail in the provided information (e.g., failure to distinguish between marine and freshwater production and specific feed used), limited differentiation between total production of a country, production within the OSPAR Convention Area, and production within areas affected by eutrophication. Additionally, there were differences in the quality and accuracy of supplied data, variability in calculation procedures and assessment methods used, and insufficient data. The diverse array of aquaculture systems, a large number of farms, and farmed species further complicated the comprehensive assessment of aquaculture production and nutrient discharges. Furthermore, there was a lack of uniformity in technical equipment used, such as cleaning and filtration systems, and farm-specific feed and feeding techniques employed (OSPAR, 2000).

Currently, there are no inventories with specific quality control and quality assurance (QA/QC) guidelines for non-point source releases from aquaculture activities. However, other resources like the International Plant Protection Convention (IPPC) Guidelines for National Greenhouse Gas Inventories can provide valuable insights into relevant QA/QC and verification processes for future pollutant release inventories from APFs. These include documentation of raw data used, assumptions made, calculation steps, and communication protocols. Maintaining good record-keeping practices is essential to ensure replicability, clarity, consistency, and comparability in pollutant inventories (OSPAR, 2000; IPPC, 2019; OECD, 2021b). These practices are crucial for maintaining data integrity and enhancing the reliability of assessments related to pollutant releases from aquaculture and their potential environmental impacts.

5. Methods and approaches for estimating pollutants releases and discharges from APFs

There are four different methods and approaches that can be employed to quantify and/or estimate pollutant discharges from APFs (Table 1). These methods include:

5.1. Nutrients (total N and total P) and carbon

High protein fish feeds contain significant amounts of nitrogen (N) and phosphorus (P), but fish retain less than 50 % of these nutrients in their bodies (Piedrahita, 2003). Studies have shown that N and P retention varies between 10 % and 49 % (N) and 17 % to 40 % (P) on average, depending on the fish species (Boyd, 2003; Piedrahita, 2003; Dauda et al., 2019). Piedrahita (2003) investigated N and P quantities in fish excreta and found that they contain 37 % to 72 % (N) and 1 % to 62

Table 1
Commonly used methods and approaches to assess pollutants discharges from APFs.

Method	Description	References
Direct measurement	involves directly measuring the concentrations of pollutants in the discharge water. It provides real-time data on pollutants levels and allows for accurate estimations of their discharges	Environment Australia, 2001; Olsen et al., 2008; Koçer et al., 2013
Mass balance	involves calculating pollutant inputs and outputs within the entire fish farm system and considers factors such are feed content, the assimilation by the fish, and pollutant losses through feces, uneaten feed, and water exchange.	Foy and Rosell, 1991; Environment Australia, 2001; Olsen et al., 2008
Modeling approaches	Application of integrated dynamic mathematical models and various numerical simulations to simulate farm operations and estimate release concentrations, pollutants dynamics, assimilation in biomass, energy conservation, farm location, accumulation and spread in sediments.	Cho and Bureau, 1998; Yakushev et al. (2020); Chary et al., 2022; Sævik et al., 2022
Biomass-based approaches	Based on the biomass of fish being produced, taking into account the nutrient content of the fish, growth rates, duration of the production cycle.	OSPAR, 2000; USEPA (2004); Olsen et al. (2008); Føre et al., 2018.

% (P), respectively. N is primarily excreted in dissolved form as ammonia, while P is excreted as particulate matter (Dauda et al., 2019). Nederlof et al. (2021) studied waste characteristics and nutrient retention efficiencies in integrated multi-trophic aquaculture, reporting that mass balance models indicate 39 % to 63 % N, 18 % to 30 % P, and 39 % to 70 % C in feed are released as inorganic waste. Verdegem (2013) documented that global aquaculture production of finfish and crustaceans in 2008 resulted in an environmental loading of 1.7 million metric tons of N and 0.46 million metric tons of P. He emphasized that cage aquaculture directly discharges nutrients into the environment, and mitigation measures should be developed and shared equally among all polluters involved (Verdegem, 2013).

The Australian Environmental Protection Agency proposed direct measurement and mass balance methods for assessing nutrient discharges from APFs in their country (Environment Australia, 2001).

1) To estimate nutrient releases from temperate water finfish in semi-closed and closed aquaculture systems they proposed direct method as following:

$$T_{N+P} = E_{N/P} {}^{*} F_{A} \tag{5.1}$$

where:

T_{N+P} = loading of total N and P to water (t/year).
$E_{N/P}$ = N and P concentration in effluent (mg/L).
F_A = conversion factor (the value is not provided in the document).

2) For marine and freshwater land-based fish farming employing semi-open systems they recommended mass balance method:

$$T_{N+P} = (F_{N+P} {}^{*} FCR) - (A_{N+P}) \tag{5.2}$$

where:

T_{N+P} = loading of total N and P to water (kg/ton fish produced).
FN + P = total N and P in feed[1] (kg/ton).
FCR = feed conversion rate (dimensionless).
AN + P = N and P converted to fish biomass (kg/ton).

The feed conversion ratio (FCR) is defined as the ratio of feed intake to fish biomass growth (Eq. (5.3)). It measures the feeding efficiency and profitability in aquaculture production (USA EPA, 2004; Naylor et al., 2009; Kause et al., 2022).

$$\text{FCR} = \text{Dry weight of feed applied/Wet weight of fish gained} \tag{5.3}$$

Fry et al. (2018) brought attention to the limitations of using Feed Conversion Ratio (FCR) as the sole measure of efficiency in aquaculture. FCR only considers the weight of feed inputs without accounting for factors like feed nutritional content, inedible portions of the animal, or the nutritional quality of the final product. To address this, the researchers conducted a comprehensive review and identified 13 different approaches to measure aquatic animal production efficiency beyond FCR. In their study, they calculated protein and calorie retention typical of commercial production for various farmed aquatic and terrestrial animals, including common carp (*cyprinus carpio*), grass carp (*ctenopharyngodon idella*), channel catfish (*ictalurus punctatus*), pangas catfish (*pangasius pangasius*), Atlantic salmon (*salmo salar*), rainbow trout (*oncorhynchus mykiss*), giant tiger prawn (*penaeus monodon*), whiteleg shrimp (*litopenaeus vannamei*), tilapia (*oreochromis niloticus*, and other cichlids). To achieve this, data on FCRs, feed composition, yield/edible portion, and nutritional profiles of the edible flesh were collected from various sources. Using these data, they proposed equations and data collection methods necessary to fill in each variable, enabling the calculation of protein and calorie retention for the selected aquaculture species as shown:

$$\text{Protein retention} = (\text{g protein in edible portion})/(\text{g protein in feed}) \tag{5.4}$$

$$\text{Calorie retention} = (\text{calories in edible portion})/\text{calories in feed} \tag{5.5}$$

The mass balance method based on the FCR value and the nutrient contents of the feed and the fish was previously proposed by Foy and Rosell (1991). They used the term "nutrient loss rate" for nutrients discharge to water (T_{N+P}, Eq. (5.1)), FEED for F_{N+P} = total N and P in feed and FISH for A_{N+P} = N and P converted to fish biomass, Eq. (5.2).

$$\text{Nutrient Loss Rate} = (\text{FCR} \times \text{FEED}) - \text{FISH} \tag{5.6}$$

where:

Nutrient Loss Rate = nutrient loss rate (kg/ton of fish produced);
FEED = nutrient content of the feed in kg/ton;
FCR = feed conversion rate (dimensionless).
FISH = nutrient content in fish in kg/ton.

The OSPAR Guidelines (OSPAR, 2000) suggested calculation based on nutrients content in a feed (N_{feed}) which are equal to the sum of nutrients converted to fish biomass (N_{fish}) and unconverted nutrients released into the water (N_{rel}):

$$N_{feed} = N_{fish} + N_{rel} \tag{5.7}$$

When estimating N_{feed} and N_{fish}, data from two sources are used: i) the German Environment Agency (Umweltbundesamt – UBA) provides information indicating that approximately 25 % of the nutrients present in the feed are converted into biomass by the cultured organisms, while the remaining 75 % is discharged into the environment; and ii) Handy and Poxton (1993), who estimated that between 52 and 95 % of N added to aquaculture systems as feed ultimately ends up being released into the environment.

In the US, the EPA (2004) used the feed-to-pollutant conversion factors to estimate an untreated or "raw pollutant loading (RPL)" as following:

$$\text{RPL} = \text{FI}_{A} {}^{*} \text{F}_{t}\text{P conversion factor} \tag{5.8}$$

where:

RPL = the pollutant load (i.e., TSS, BOD, TN, TP) in pounds (or tons)/year;

[1] The proportion of P and N in the feed should be obtained directly from the producers

FI_A is Annual feed input = the amount of feed distributed to the production system (pounds or tons/year);

F_tP is Feed-to-pollutant conversion factor = feed inputs (i.e., TSS, BOD, TN, TP in pounds (tons) of pollutant/pound (ton) of feed).

In a study conducted by Koçer et al. (2013) in Turkey, waste loading from three land-based trout farms with different annual production rates (250, 750, and 2500 t yr − 1) into a regulated stream was monitored. The researchers calculated the differences between outflow and inflow concentrations for various parameters, including temperature, dissolved oxygen, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (N), and phosphorus (P). Additionally, they estimated the nutrient loading from nine land-based trout farms into the Mediterranean Sea using simple mass-balance equations:

$$C = L/Q_1 \tag{5.9}$$

where:

C = average annual concentration of TSS, TN and TP (kg m^{-3}),

Q_1 = the total annual flow rates in the receiving stream (m^3 yr^{-1}).

L = the total annual loading into the receiving stream reach from fish production (kg yr^{-1}), and is calculated as.

$$L = L_f/P_f \tag{5.10}$$

where:

L_f = the estimated waste loads per fish mass (kg t^{-1} of fish produced).

P_f = total annual fish production (ton $year^{-1}$).

The authors found strong correlations between predicted and measured concentrations of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) in the effluents of the monitored trout farms. The predicted nutrient loadings using the nutritional method closely matched the measured values, with 44.3 kg of nitrogen (N) and 8.4 kg of phosphorus (P) per ton of fish produced, compared to the measured values of 43.9 kg N and 8.8 kg P per ton of fish produced. These results led the authors to emphasize that land-based trout farms can significantly contribute to nutrient and solid loading in coastal ecosystems.

In another study by Azevedo et al. (2011), the Fish-PrFEQ feed requirement and waste output model was utilized to estimate the loading of total solids (both fecal and feed origin) (TS), solid phosphorus (SP), solid nitrogen (SN), and dissolved phosphorus (DP) and nitrogen (DN) from Canadian rainbow trout farmed fish over a two-year period. The researchers used measured data of nutrient contents and nutrient digestibility of the commercial feed as inputs to the model to calculate nutrient intake and digestible nutrient intake, respectively. The predictions of nutrient loading were compared with measured nutrient concentrations in lake water. The findings revealed that over 60 % of the phosphorus output from the cage was in solid form, while over 65 % of the total nitrogen waste from the cage farm was excreted as ammonia.

Olsen et al. (2008) proposed a series of simple equations based on Mass balance in a Food-Fish-Waste system:

$$I = A + F = G + R + F \tag{5.11}$$

where:

I = the food consumed; A = assimilated food, or uptake in tissues; F = defecation; R = respiration, and G = growth and reproduction (all in terms of carbon or energy).

The corresponding nutrient balance can be calculated using the analogue equation:

$$I_{N,P} = A_{N,P} + F_{N,P} = G_{N,P} + E_{N,P} + F_{N,P} \tag{5.12}$$

where:

where excretion of N and P ($E_{N,P}$) replaces respiration.

The authors defined assimilation efficiency (AE) as:

$$AE = A/I \tag{5.13}$$

and the growth efficiency (GE) as:

$$GE = G/I \tag{5.14}$$

where:

GE = expresses the efficiency of ingested food conversion to new biomass.

I = the food consumed (defined in Eq. (5.11))

G = growth and reproduction (defined in Eq. (5.11)).

The authors underlined that the knowledge of AE of C, N, and P and the stoichiometric C:N:P composition of produced fish and feed, are fundamental for estimating nutrient and carbon intake, and metabolism of cultured fish in APFs (Olsen et al., 2008).

They further proposed that total wastes of carbon (TL_C) and nutrients (TL_{NP}) generated by cultured fish can be derived from:

$$TL_C = I - G = R + F \tag{5.15}$$

$$TL_{NP} = I_{NP} - G_{NP} = E_{NP} + F_{NP} \tag{5.16}$$

where I, G, R, F are defined in Eq. (5.11) as:

I = the food consumed; G = growth and reproduction; R = respiration and F = defecation;

E_{NP} = excretion of N and P (defined in Eq. (5.12)).

Fish respiration results in a release of inorganic CO_2, and the emission of organic carbon wastes (L_{OC}) and can be estimated as:

$$L_{OC} = I - A = I\,(1 - AE) \tag{5.17}$$

where:

AE = assimilation efficiency of carbon or energy which according to Olsen et al. (2008) can be obtained from literature and/or from feed companies.

As there is no formal way to distinguish dissolved organic components (DOC) from the particulate organic waste components (POC) from dissolved feces, organic nutrient wastes (L_{ONP}) can be estimated as.

$$L_{ONP} = I_{NP} - A_{NP} = I_{NP}\,(1 - AE_{NP}) \tag{5.18}$$

where:

I_{NP} = N and P consumed and can be estimated as total feed intake multiplied by feed N and P contents.

A_{NP} = N and P in assimilated food, or in tissues.

AE_{NP} = assimilation efficiency for N and P.

The inorganic N and P release from the fish (L_{INP}) can be estimated as the difference between assimilation and production:

$$L_{INP} = A_{NP} - G_{NP} = (I_{NP} * AE_{NP}) - G_{NP} \tag{5.19}$$

where:

G_{NP} = N and P content in fish calculated as produced fish weight multiplied by N and P contents;

A_{NP}, I_{NP} and AE_{NP} are defined in Eq. (5.18).

5.2. Metals (copper and, zinc, mercury and cadmium)

The scientific literature contains numerous studies discussing the toxicity, distribution, and adverse effects of copper (Cu) and zinc (Zn) on water quality and sediments beneath aquatic animal production facilities (AFPs) (e.g. Clement et al., 2010; Sneddon and Tremblay, 2011; Grigorakis and Rigos, 2011; Guardiola et al., 2012; Simpson et al., 2013; Nikolaou et al., 2014; Hamoutene et al., 2018). However, information about estimation techniques to quantify pollution discharges from these metals is limited (Dean et al., 2007; Earley et al., 2014; Earley et al., 2020).

Dean et al. (2007) conducted an extensive sediment sampling study to investigate the spatial distribution of Zn, Cu, Hg and Cd in sediments around a cage farm in Scotland. For each sediment sample, they determined concentrations of each metal and converted them to mass of metal per unit area (g m-2) using the following method:

$$\text{Inventory}\ \left(\text{gm}^{-2}\right) = \frac{\sum_{i=1}^{n=y}([metal]i\,dry\ wt.)}{Area} \tag{5.20}$$

where:

$[\text{metal}]_i$ = metal concentration in the ith slice (mg g^{-1});

dry wt. = dry weight of full slice (g);

area = $r^2\pi$, r = core diameter (m^{-2}).

y = depth of sediment core.

To estimate the budget of metals, the total mass of metals present in the feed and fish was determined by using information on the feed and biomass input, as well as the Feed Conversion Ratio (FCR).

In the studies conducted by Earley et al. (2014, 2020), they investigated the environmental loading and rates of metal leaching from Cu alloy and coated-nylon net materials over a year-long period (365 days) in San Diego Bay, California, USA. They estimated the environmental life cycle loadings of copper (Cu) by integrating data on the leaching rates from a typical aquaculture farming pen (30 × 30 × 12 m) and a generic lifecycle model. They proposed the following Eq. (5.21) to calculate the cumulative loading (CL) of copper over a given time interval (x0 to xn), which was approximated from leach rate measurements (R):

$$\text{CL}\ x_0, x_n = \sum\nolimits_{x_0}^{x_n}(x_1 - x_0)\frac{R(x_0)+R(x_1)}{2} + (x_2 - x_1)\frac{R(x_1)+R(x_2)}{2} + (x_n - x_{n-1})\frac{R(x_{n-1})+R(x_n)}{2} \tag{5.21}$$

where:

CL x_0, x_n = cumulative Cu loading (μg cm^{-2}) from day x_0 through x_n;

x_n = a series of consecutive time points (days) during which release rate measurements were made and.

$R(x_n)$ = the measured release rate (μg cm^{-2} d^{-1}) for time point x_n.

In addition, they observed a consistent pattern in Cu release rates where an initial concentration spike is followed by a gradual decline to reach either a sustained low level or a pseudo-steady state (PSS) and proposed the following equation to calculate PSS:

$$\text{PSS}_{\text{xa,xn}} = \frac{\text{CL}xa, xn}{(x_n - x_a)} \tag{5.22}$$

where:

$PSS_{xa,xn}$ = the pseudo steady state loading rate (μg cm^{-2} d^{-1}), which occurs after day x_a;

$\text{CL}_{xa,xn}$ = the cumulative Cu loading (μg cm-2) from day x_a through x_n;

x_a=the time after which the Cu release rates asymptote to PSS.

Furthermore, the following Eq. (5.23) was suggested to estimate the cumulative Cu loading during the initial release period:

$$\text{IL}_{\text{x0,xa}} = \text{CL}_{\text{x0,xa}} \tag{5.23}$$

where:

$IL_{x0,xa}$ = the initial release loading (μg cm^{-2}), which occurs before day x_a:

CL $_{x0,xa}$ = the cumulative copper loading (μg cm-2) from day x_0 through x_a;

The total Cu loading based on a materials life cycle was then estimated using the above variables according to Eq. (5.24):

$$\text{Life Cycle Loading}_{\text{s,f}} = \left(\left(\text{IL}_{\text{x0,xn}}\right) \times \left(\sum E_{cleaning} + \sum E_{replacement}\right)\right) + \left(\text{PSS} \times \sum D_{PSS}\right) \tag{5.24}$$

where:

Life Cycle $\text{Loading}_{\text{s,f}}$ = Cumulative release of Cu (μg cm^{-2}), between time points x_s and x_f, the time over which the material is exposed to water;

$\Sigma E_{cleaning}$= the total number of material cleaning events over a given life cycle period;

ΣD_{PSS}= the total number of days at which PSS releases are anticipated to occur.

$\Sigma E_{replacement}$= the total number of regularly scheduled material replacement events over a given life cycle period (which includes the initial placement of material).

5.3. Pesticides and persistent organic chemicals

Various authors have employed modeling and biomass-based approaches (Table 1) to predict the bioaccumulation of organic chemicals (OC) in aquatic food-webs within freshwater environments (Gobas, 1993; Mackay and Fraser, 2000; Arnot and Gobas, 2004; USEPA, 2021). In a comprehensive literature review, Mackay and Fraser (2000) focused on mechanisms and models used for predicting and estimating the bioaccumulation of persistent organic chemicals (POPs) in fish. They proposed a new empirical model for determining bioconcentration and a mechanistic model for estimating bioaccumulation. The authors emphasized that bioaccumulation assessments are particularly relevant for estimating the discharges of pesticides and POPs from aquatic production facilities (APFs). However, they did not provide specific recommendations on how to calculate these releases, indicating a need for further research and development in this area.

To determine the chemical content of organic compounds in feed, we propose a similar approach to the OSPAR (2000) equation used for assessing nutrient loading from APFs (Eq. (5.7)):

$$\text{OC}_{\text{feed}} = \text{OC}_{\text{fish}} + \text{OC}_{\text{rel}} \tag{5.25}$$

where:

OC_{feed} = organic chemical content in feed.

OCfish = Organic chemical content converted to fish biomass (OCfish), which can be estimated using models proposed by Mackay and Fraser (2000).

OCrel = unconverted organic chemical released into the water.

In 2009, scientists from the US EPA Office of Pesticide Programs' Environmental Fate and Effects Division introduced the KABAM (KOW (based) Aquatic Bioaccumulation Model) to evaluate the potential bioaccumulation of hydrophobic organic pesticides in freshwater aquatic food webs (Arnot and Gobas, 2004; USEPA, 2022). The model provides a systematic and standardized approach to assess the bioaccumulation of these pesticides in aquatic organisms. For more in-depth information about the KABAM model, including its methodology and application, interested readers can refer to the detailed description available on the US EPA website (USEPA, 2023). This model represents a valuable tool for regulatory agencies and researchers to assess the potential risks associated with the bioaccumulation of hydrophobic organic pesticides in freshwater ecosystems.

5.4. Microplastics

To date, there has been a lack of robust methods for observing and quantifying microplastics (MPs) in aquatic environments and organisms

(Lusher et al., 2017). The Food and Agriculture Organization (FAO) conducted a comprehensive study on MPs in fisheries and aquaculture, identifying significant knowledge gaps, particularly concerning the occurrence of smaller-sized microplastics (less than 150 μm) in aquatic environments. They also predicted a continuous increase in MPs contamination in aquatic ecosystems in the foreseeable future.

In a recent review by Wu et al. (2023), they extensively covered the topic of microplastic pollution in aquaculture. The researchers focused on sources, environmental and human health impacts, and current removal strategies. They highlighted that a considerable portion of MPs found in aquaculture areas, especially coastal regions, originates from external sources, notably local rivers. Within aquatic production facilities (APFs), primary sources of MPs include fish meals, feed, and packaging of aquaculture products. The review also discussed various methods for field monitoring of MPs, including the use of novel portable MP monitoring systems like Raman spectrophotometry and remote sensing technology.

With the increasing availability of equipment for field monitoring and quantification of MPs in water columns and solid materials, it is now possible to estimate MPs releases from APFs by combining direct measurements and mass balance approaches (see Table 1). APFs owners should collect data and keep records of plastic packaging contents, as well as MPs content in the feed. Additionally, they should perform measurements of MPs content and quantity in the water column within their facilities and at least three different distances (e.g., 5, 15, 25 m) from the APFs at the beginning and end of the production cycle. Based on these data, an equation analogous to 5.7 could be employed to estimate MPs releases from the APFs as follows:

$$MP_{feed} = MP_{fish} + MP_{rel} \quad (5.26)$$

where:

MP_{feed} = MPs content in the feed.
MP_{fish} = MP in the fish biomass.
MP_{rel} = MP released in the APF water column.

6. Critical perspectives and recommendations

Recent scientific evidence highlights the significant role of APFs in contributing to NPS pollution. Surprisingly, there is a lack of comprehensive guidance documents that clarify the methodologies and techniques for assessing this type of pollution arising from aquaculture operations. Moreover, the current Pollution Release and Transfer Registers (PRTRs) do not require reporting from NPS aquaculture pollution. It is crucial to change this status quo, as addressing this gap is essential to ensure the sustainability of aquaculture production practices and the effective environmental management of freshwater and marine resources. Therefore, it is imperative to develop methodologies and techniques for quantifying these discharges and to include requirements for reporting NPS pollution in PRTRs.

Based on our review, we propose that APF owners and managers include the following information in their PRTRs:

1. Facility details (e.g., location, surface area, aquaculture production type, species farmed, monthly or annual production capacity).
2. Feeding regimes and rates.
3. Feed and feed supplements contents (e.g., nitrogen, phosphorus, organic matter, protein, percent of plant-based materials used).
4. Feed conversion ratio.
5. Use of veterinary medicinal products.
6. Subsequently, APF owners and managers should apply relevant eqs. (5.1 to 5.26) to estimate pollutant releases and transfers from their operations.
7. In addition, regular assessment and monitoring of the feed and feed supplements content should be performed by the designated authorities at the local, regional and national levels.

Identifying and estimating the release of microplastics (MPs) from APFs represent critical steps in addressing the existing knowledge gap and gaining a better understanding of the presence and distribution of MPs in freshwater and marine aquaculture environments. Ensuring transparency and providing information about MPs in fish biomass is essential for safeguarding human health against the harmful effects of these substances. This is particularly crucial for APFs in South and Southeast Asia, which are the world's leading aquaculture producers. These countries also rank among the largest contributors to plastic waste in the oceans (Wicaksono, 2023). Monitoring and quantifying the release of MPs from APFs will provide valuable insights for the development and implementation of appropriate regulations and best management practices aimed at reducing MPs emissions. This will ultimately serve to protect both the environment and consumers of aquaculture products.

7. Conclusions

This review represents the first comprehensive inventory of existing techniques, methods, and approaches to estimate NPS pollution releases to water from aquaculture production facilities (APFs). Throughout the research process, several important findings have emerged:

1. Currently, there are very few methods available for estimating releases of pollutants from APFs. Moreover, the existing methods are primarily focused on nutrients, total organic carbon, and copper, while approaches for estimating pesticides, persistent organic pollutants (POPs), and microplastics have not been adequately developed.
2. Guidance documents and inventories on both point and NPS pollutant releases from aquaculture production facilities are lacking, and those that do exist are outdated, with some dating back over 20 years. This highlights the need for updated and more comprehensive guidelines to assess pollution from APFs.
3. The review proposed two simple equations for estimating releases of pesticides, POPs, and microplastics from APFs. However, further investigations and research are essential to develop robust methods and techniques for accurately estimating pollutant releases from APFs, especially for the aforementioned pollutants.

This inventory can serve as a valuable guide for acquiring data and developing specific procedures to estimate and assess pollutant loading from APFs. Knowledge of pollutant loading from APFs will enable their inclusion in legal regulatory instruments such as the National Baseline Budget of pollutants (NBB) and Pollutant Release and Transfer Registers (PRTRs). Publicly disclosed information in PRTRs will promote transparency, facilitate informed decision-making, and support the development of regulatory frameworks to effectively reduce, mitigate, and control pollution originating from APFs.

By advancing our understanding and monitoring of pollutant releases from APFs, we can take proactive measures to protect aquatic ecosystems, preserve water quality, and ensure the safety of aquatic food products for human consumption. This will contribute to sustainable aquaculture practices and the conservation of the environment for future generations.

Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

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