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Microplastics in aquafeeds: Occurrence, sources, effects and considerations for aquatic food production

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ABSTRACT

Microplastics (MPs) contamination in aquafeeds poses a significant threat to food safety and security in aquaculture. This paper aims to comprehensively review research progress in this field, systematically analyze relevant topical issues, and reveal current gaps and future research priorities. This review firstly summarizes the analytical techniques for the separation and identification of MPs in aquafeeds. It then introduces the occurrence and sources of MPs in aquafeeds. Subsequently, the impacts of MPs on the growth, health of aquatic organisms, and the safety of aquatic food are discussed. Finally, this study provides feasible mitigation strategies targeting major contamination pathways. Despite the widespread presence of MPs in aquafeeds, research in this area remains insufficiently addressed. The lack of standardized analytical methods poses challenges to safety assessments and policy-making.

1. Introduction

Aquaculture has assumed an increasingly crucial role in fulfilling human dietary needs. In 2020, global aquaculture production accounted for 49.2 % of the total fisheries output, making a substantial increase from 19.7 % in the 1990s [1]. By 2032, global fish production is projected to reach 202 million tonnes (Mt), with aquaculture anticipated to constitute 55 % of this total [2]. Notably, more than half of the production in cultured animals relies on aquafeeds [3], highlighting the pivotal role of high-quality and consistent aquafeed supplies in fostering the sustainable growth of aquaculture. Estimated by major cultured species, global aquafeed consumption was 51.23 Mt in 2017, and is expected to reach 73.15 Mt by 2025 [4]. Unlike other animal feeds, aquafeeds typically require fishmeal (FM) to fulfill the nutritional needs of aquatic organisms [5]. With the spike in FM prices during the 2000s [6], an array of alternative ingredients emerged, such as poultry by-product meal, soybean meal, cottonseed meal, corn meal, and others [7]. The safety of aquafeeds and ingredients has always been emphasized because historically there have been a number of food safety problems caused by the contamination of human food by feeds or animal production chains, such as the dioxin scandal in Belgium, mad cow disease in the United Kingdom, and the wheat adulteration melamine incident in China [7]. Disturbingly, the global widespread contaminant microplastics (MPs) have recently been detected in aquafeeds and various feed ingredients [8–10].

MPs, measuring less than 5 mm, were first discovered in the ocean in 2004, prompting widespread attention [11]. Since 1950, the production and consumption of plastics has grown exponentially, with the current annual global plastic production of about 430 Mt [12], while generating 400 Mt of plastic waste [13]. Over 80 % of plastic waste was incinerated, dumped in landfills or released into the natural environment [14]. In 2023, approximately 23.53 Mt of plastics were globally released into the environment [15]. MPs contamination has been involved in the environment of human food production, with estimated global reserves of 1.5–6.6 Mt in agricultural soils [16] and 0.9–2.5 Mt on the ocean surface [17]. Due to their persistent nature, abandoned plastic waste often takes decades or even centuries to degrade [18]. Over time, these discarded plastics fragment into smaller particles through weathering, mechanical

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forces, and degradation, complicating the cleanup process and increasing their risks [19]. These tiny particles can also be part of atmospheric dust, transported to various corners of the world [20]. Rochman and Hoellein argued that MPs are globally transferred, akin to the biogeochemical cycles of nitrogen, carbon, and water [21].

MPs found in aquafeeds present a potential threat to both the sustainability of aquaculture and human food safety. Ingestion serves as a primary pathway for MPs to enter an organism's body, exhibiting diverse effects on the growth of aquatic animals. For instance, exposure through the diet inhibited the growth of various species, such as discus fish (*Symphysodon aequifasciatus*) [22], walking catfish (*Clarias batrachus*) [23], yellow river carp (*Cyprinus carpio* var.) [24], and langoustine (*Nephrops norvegicus*) [25]. Additionally, emerging evidence indicates that MPs can induce health impairments in aquatic species, including neurotoxicity, oxidative stress, disturbances in intestinal flora, histological damage, and even increased mortality, potentially reducing production in aquaculture [22,26,27]. Moreover, the translocation of ingested MPs, along with other contaminants such as heavy metals, into the edible tissues of aquatic animals, poses additional concerns for the safety of aquatic products [28].

Here, 92 original peer-reviewed papers are systematically reviewed, overwhelmingly published within the last 5 years. This paper presents the first comprehensive review on MPs contamination in aquafeeds, revealing current research advancements and offering insights for future investigations and remedial strategies. We first illustrate the methods employed for the extraction and isolation of MPs in aquafeeds and unveil the occurrence, characteristics, and sources of MPs in aquafeeds. We further delve into elucidating the impact of MPs on aquatic animal health and aquatic food safety. Finally, pragmatic recommendations aimed at managing and mitigating contamination are provided.

2. Challenges in MPs analysis within aquafeeds

Analyzing MPs within aquafeeds faces notable challenges due to the complex composition of aquafeeds [5]. Research on MPs in environmental samples typically involves sampling, pretreatment, and qualitative and quantitative analyses [29]. Unlike water samples, which require only density separation and filtration for further analysis [29], extracting MPs from aquafeeds or ingredients requires an additional digestion process to remove organic impurities that may interfere with the identification of MPs [30]. Table 1 summarizes the methods of digestion, density separation, filtration and characterization regarding the study of MPs in aquafeeds or ingredients.

2.1. Digestion

The main challenge lies in efficiently digesting organic matter in feed samples while not damaging MPs, both in quantity and appearance. Current digestion methods for aquafeeds typically draw upon techniques used for similar biological samples [36]. Digesting bio-organic matter involves various chemical solutions, ranging from concentrated HNO_3 [39] to weaker oxidizing agents like H_2O_2 [33], or alkaline treatments such as KOH [35]. The strong oxidizing agents has been found to cause degradation of various types of polymers [39], whereas weakly alkaline or oxidizing treatments tend to be more effective without causing substantial damage to synthetic polymers [33,35]. As shown in Table 1, most of the digestion solutions used in the studies were weakly basic or weaker oxidizing agents, including 10 % KOH [9,10,30,35,36] and 30 % H_2O_2 [10,33,38]. Nevertheless, the strong oxidizing agents 65 % HNO_3 and 30 % KOH:NaClO were used in the studies of Siddique et al. [8] and Gundogdu et al. [37], respectively. It has been demonstrated that the digestion method affects the recovery of MPs from feed samples [40].

Enzymatic digestion is a promising method that effectively removes proteins and fats, the main components of aquafeeds [41]. Cole et al. demonstrated that Proteinase-K treatment digested over 97 % of the marine organism samples, while digestion efficiencies of 1 M and 2 M NaOH were 90.0 ± 2.9 % and 85.0 ± 5.0 %, respectively, and those of 1 M and 2 M hydrochloric acid were 82.6 % ± 3.7 % and 72.1 ± 9.2 %, respectively [42]. Notably, enzyme treatment preserved the morphology and appearance of MPs, whereas alkaline treatment caused partial destruction of nylon fibers, melting of polyethylene fragments, and yellowing of uPVC particles [42]. Maintaining the undamaged appearance of MPs particles aids in their identification and tracking of their sources. Despite these advantages, enzymatic treatments may not be as favorable regarding time and cost compared to chemical treatments.

Table 1
Methods for extraction and identification of MPs in aquafeeds/ingredients.

Sample types	Digestion	Separation	Filter aperture	Verification	References
Aquafeed	10 % KOH	NaCl	0.45 μm	FTIR	[30]
	–	NaBr	0.22 μm	–	[31]
	65 % HNO_3	NaI	45.30 μm	FTIR	[8]
	–	NaCl	63.00 μm	ATR-FTIR	[32]
	30 % H_2O_2	–	1.20 μm	μFTIR	[33]
Feed ingredients					
FM	–	NaCl	55.00 μm	FTIR	[34]
FM	10 % KOH	NaI	8.00 μm	Raman	[35]
FM	10 % KOH	NaI	8.00 μm	FTIR	[36]
FM	10%KOH	$ZnCl_2$	0.20 μm	μFTIR	[9]
FM	10 % KOH and 30 % H_2O_2	–	1.00 μm	Raman	[10]
FM	30 % KOH: NaClO	NaI	0.45 μm	μFTIR	[37]
FM	30 % H_2O_2	NaCl	20.00 μm	FTIR	[38]
Krill	10%KOH	$ZnCl_2$	0.20 μm	Raman	[9]
Krill	30 % KOH: NaClO	NaI	0.45 μm	μFTIR	[37]
Shrimp meal	30 % H_2O_2	NaCl	20.00 μm	FTIR	[38]
Soybean meal	10%KOH	$ZnCl_2$	0.20 μm	FTIR	[9]
Soybean meal	10 % KOH	NaI	8.00 μm	FTIR	[35]
Squid	10%KOH	$ZnCl_2$	0.20 μm	FTIR	[9]

2.2. Density separation

Density separation is a common method of separating MPs from sediments and has also been applied to feed samples, commonly using saturated salt solutions. The densities of common MPs (e.g., polypropylene (PP), polyethylene (PE), polyamide (PA), Polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PU)) range from 0.90 to 1.58 g/cm^3 [43], while different salt solutions may affect the effectiveness of separation due to their density levels. As shown in Table 1, a variety of salt solutions were employed, including NaCl [30,32,34,38], NaBr [31], NaI [35–37], and $ZnCl_2$ [9]. The most used solution was saturated NaCl, probably due to its availability, low price and non-toxicity. However, the density of saturated NaCl is about 1.2 g/cm^3, which is considered insufficient for the separation of higher-density MPs, such as PVC (1.40 g/cm^3) [44]. Relatively, higher-density saturated solutions of NaBr, NaI, and $ZnCl_2$ are commonly regarded as more efficient density separators for MPs [45]. In addition to considering recovery efficiency, it is imperative to also take into account the environmental impact and cost of the solution [46]. Among the three solutions, NaI is more expensive and $ZnCl_2$ is more environmentally hazardous [46], hence NaBr is the more desirable solution.

2.3. Necessity of standardized methods for analyzing MPs

Standardized methodologies are critical when assessing the abundance of MPs in specific biological samples as the varied techniques used to extract, isolate, and characterize MPs can create challenges in the comparison of results and reduce overall credibility. Way et al. compared five methods of extracting MPs from FM, revealing that the highest recovery (66.3 %) of MPs was achieved using dispersant and KOH digestion with $CaCl_2$ density separation [40]. However, even with this method of separation, the type of samples and polymers significantly affected the recovery of MPs, emphasizing the necessity of optimizing the separation reagents and characterizing the samples prior to separation [40]. In addition, the filter apertures used in these studies varied (Table 1), and those using larger apertures (e.g., 45.30 μm [8], 63.00 μm [32], 55.00 μm [34], 20.00 μm [38]) inevitably left out the smaller-sized MPs. In terms of characterization methods, Fourier transform infrared (FTIR) and Raman are used in the study of MPs in aquafeeds and ingredients (Table 1). The applicability of these two types of methods tends to depend on the characteristics of the target MPs (e.g., size, appearance, and sample purity) [47]. As proposed by Hermsen et al., a reference standard for studies of MPs includes sampling methods, sample volume, handling, and storage protocols, laboratory preparation, air cleanliness, negative and positive controls, target components, sample (pre)handling, and polymer identification [48]. Studies lacking certain crucial information risk being deemed unreliable [48].

3. Occurrence and characteristics of MPs in aquafeeds

3.1. Occurrence of MPs in aquafeeds

To date, there have been five reports on MPs in aquafeeds, and all 47 samples have detected MPs, highlighting the prevalence of contamination. As indicated in Table 2, the abundance of MPs in aquafeed samples investigated across multiple studies varied widely (28–9150 MP/kg), indicating that study results are influenced by various factors beyond research methods. Firstly, the abundance of MPs in aquafeeds may be related to the degree of contamination of their place of origin. It was found that all feed samples from Bangladesh exhibited higher MPs concentrations, ranging from 141.42 to 9150 MP/kg [8,30,31]. Conversely, feed samples from Denmark showed lower MPs concentrations, with 28 MP/kg [32]. The global distribution and abundance of MPs show that the severity of pollution in Asia is greater than in Europe [49], and that MPs in the environment probably enter the production of aquafeeds through various pathways. It was found that the number of MPs in feed ingredient samples from Asia was much higher than in samples from Europe, further supporting this view [10].

In addition, the abundance of MPs in diets for different stages of fish varied considerably, with the highest at 1372.22 MP/kg for juvenile feeds and the lowest at 141.42 MP/kg for adult feeds [8]. Similarly, Muhib and Rahman reported that the lowest abundance of MPs was found in nursery stage fish feed at 883.33 ± 39.71 MP/kg and the highest abundance of MPs was found in finisher stage fish feed at 9150 ± 37.37 MP/kg [30]. The results of these two studies reflect that the abundance of MPs in aquafeeds is related to the feeds for different stages of fish. This discrepancy may be related to the feed ingredients and their

Table 2
Occurrence and characteristics of MPs in aquafeeds.

Country	Feed type	Abundance	Size	Shape	Colour	Polymers	References
Bangladesh	–	2.00 MP/g	10.08–88.38 μm	Fiber (75.92 %), fragments (16.67 %), film (16.67 %)	Blue, translucent, red, and brown	–	[31]
		5.57 MP/g		Fiber (56.41 %), fragments (28.21 %), film (15.38 %)			
Bangladesh	Fingerlings	1056.25 MP/kg	100–1500 μm (88 %), 1500–3000 μm (9 %), 3000–5000 μm (3 %)	Fiber (90 %), line (5 %), film (2 %), fragment (1 %), and foam (2 %)	Red (34 %), black (31 %), blue (19 %), green (13 %), and transparent (3 %)	PE (37.71 %), PVC (27.14 %), PP (22.08 %), and PET (13.07 %)	[8]
	Juvenile	1372.22 MP/kg					
	Adult	141.42 MP/kg					
Bangladesh	Nursey	883.33 ± 39.71 MP/kg	14–4480 μm	Filament (49.06 %)	Blue (47.17 %), transparent (37.74 %), white (9.43 %), brown (1.89 %), red (1.89 %), and grey (1.89 %)	PP (20.83 %)	[30]
	Pre-starter	1233.35 MP/kg		Film (43.24 %)	Transparent (43.24 %), blue (24.32 %), white (22.97 %), red (6.76 %), and pink (2.70 %)	PP (33.33 %)	
	Starter	2983.26 MP/kg		foam (64.81 %)	White (64.25 %), transparent (24.02 %), brown (5.59 %), blue (4.47 %), pink (1.12 %), and red (0.56 %)	PET	
	Grower	1033.14 MP/kg		foam (52.31 %)	White (52.38 %), transparent (39.68 %), brown (3.17 %), red (3.17 %), and blue (1.58 %)	PP (33.33 %)	
	Finisher	9150 ± 37.37 MP/kg		foam (55.19 %)	White (55.01 %), transparent (39.34 %), blue (2.73 %), red (1.27 %), brown (0.91 %), pink (0.73 %)	PP (35.71 %)	
Denmark	–	28 MP/kg	–	Fibers and fragments (90.73 %), flakes (6.62 %), filament (1.99 %), sphere (0.66 %)	–	PA (35.71 %), PP (21.43 %), PE, HDPE, and CPE (14.29 %)	[32]
–	–	3.93 ± 1.38 MP/g	37–4526 μm; <100 μm (32.2 %), and 150–499 μm (33.9 %)	Fragments (53.4 %), fibres (30.9 %), pellets (8.5 %), films (4.0 %)	Black (45.8 %), blue (22.9 %), transparent (3.4 %), white (1.7 %)	Phenoxy resin (33.1 %), cellulose/rayon (25.4 %), PET (11.0 %)	[33]

Note: PE, polyethylene; PVC, polyvinyl chloride; PP, polypropylene; PET, polyethylene terephthalate; HDPE, high density polyethylene; PA, polyamide; CPE, chlorinated polyethylene.

addition ratio in different types of aquafeeds, since aquatic animals require specific nutrients at various stages of growth [50]. As mentioned earlier, however, the abundance of MPs in aquafeeds may be seriously underestimated due to the current limitations in separating and recovering MPs from aquafeeds [40].

3.2. Characteristics of MPs in aquafeeds

The visual features of MPs, such as shape, colour, and size, are typically characterized using an optical microscope [8,30–33]. Siddique et al. reported that 88 % of the MPs found were predominantly in the size range of 100–1500 μm, while only 3 % of the MPs were in the size range of 3000–5000 μm [8]. Matias et al. found that the range of MPs particles identified was 37–4526 μm, with sizes <100 μm accounting for 32.2 % of the total, and 150–499 μm accounted for 33.9 % [33]. The results indicate that small-sized MPs dominate in aquafeeds. The shapes of MPs in aquafeeds include fiber, fragments, filament, film, line, flakes, sphere and foam, and the colors are blue, red, brown, black, green, transparent, white, grey, pink (Table 2). Three studies reported a majority of MPs in fiber and fragment shapes [31–33], and Siddique et al. found that fiber-shaped MPs accounted for 90 % [8], indicating that the shape of MPs in aquafeeds is predominantly fiber and fragment. Besides, Muhib and Rahman found that the predominant MPs shapes in the various types of fish feeds were different, with nursey feeds being filament, pre-starter feeds being film, and starter, grower, and finisher feeds being foam [30].

The polymer types of MPs are typically identified using FTIR, μFTIR, and ATR-FTIR (Table 1), depending on the size and morphology of the plastic samples to minimize interference. Siddique et al. identified that the polymer types of MPs in aquafeeds were dominated by PE, PVC, PP and PET [8]. In the study by Muhib and Rahman, the order of the four most abundant polymers was PP > PET > PS > Nylon-6, with PP being the most abundant in nursey, pre-starter, grower, and finisher feeds, and PET being the most abundant in starter feeds [30]. In two other studies PP, PE [32] and PET [33] were also found to be more polymer types respectively. From these limited results, it can be inferred that the most common polymers of MPs in aquafeeds include PE, PP and PET (not limited), which is similar to the findings from the survey in FM, an aquafeed ingredient [35–37]. Nevertheless, individual occurrences of the dominant polymer types were reported in all the studies (Table 2), pointing out the diversity of the sources of MPs contamination in aquafeeds.

4. Major sources of MPs in aquafeeds

Based on the characterization and identification of plastic particles in aquafeeds, the contamination of aquafeeds with MPs can be attributed to three main sources/pathways: feed ingredients, packaging materials and production processes [8,30,33]. Aquafeeds are formulated by blending various feed ingredients in specific ratios to meet the requirements of aquaculture animals [3]. These ingredients undergo a sequence of processes before being formulated into finished feed, including transportation, packaging, and production, each of which may be susceptible to contamination with MPs (Fig. 1).

4.1. Feed ingredients

4.1.1. Fishmeal (FM)

FM, a traditional protein source in aquafeed, is derived from low-value fish captured in the ocean or from fish processing waste [5].

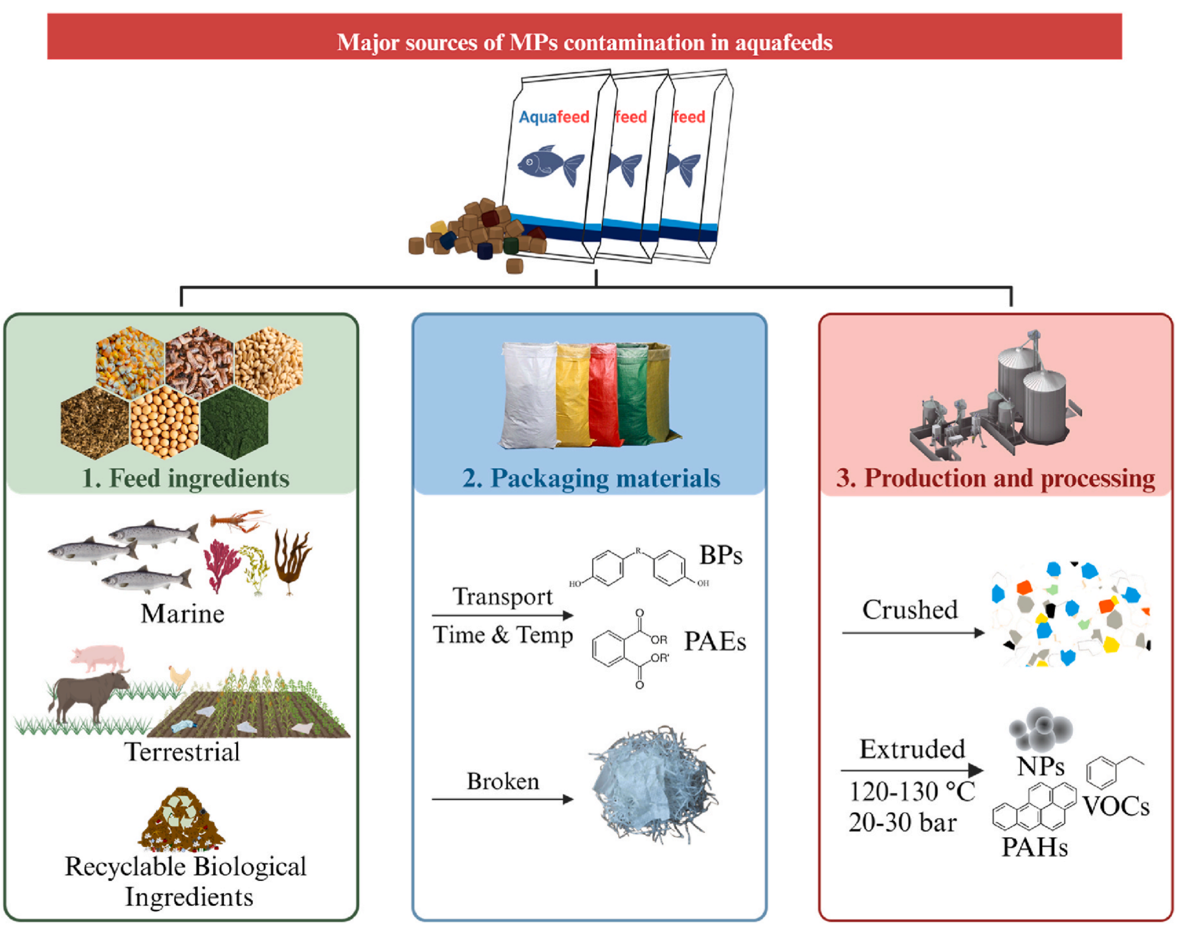

Fig. 1. Major contamination pathway of MPs in aquafeeds.

According to FAO estimates, global FM production is approximately 5 Mt, with aquaculture consuming over 27 % of this amount [1]. The presence of MPs commonly found in pelagic fish has raised concerns about contamination of aquafeed [37]. Table 3 summarizes the characteristics of MPs in FM, indicating that the predominant shapes are fragments, filaments, films and fibers, and the main polymers are PE, PP, PET and PS. Studies have investigated MPs from seawater, and characterization has revealed that the main shapes are fibers, films, fragments, and pellets, while the main polymer components are rayon, PP, PET, and PE [51,52]. The similar characteristics and polymer composition of MPs in seawater and FM confirm that FM is one of the important pathways of marine MPs transmission and a major source of MPs contamination in aquafeeds [30].

4.1.2. Terrestrial ingredients

Terrestrial ingredients can be categorized mainly into animal and plant sources [7]. Common animal-derived ingredients include meat and bone meal, poultry by-product meal, feather meal, and blood meal, which are primarily processed from by-products of livestock and poultry processing [53]. Current evidence indicates a high risk of MPs contamination in these ingredients. For instance, a survey conducted in the livestock and poultry farming systems in Southern China identified potential pathways for the contamination of MPs [54]. Furthermore, MPs were found in the lungs and feces of farmed pigs, indicating the transmission of MPs through the food chain and respiratory pathways in livestock and poultry animals [55]. Regarding plant ingredients, two reports investigated MPs contamination in soybean meal, with one indicating no contamination and the other reporting an abundance of 1.23 MP/g [9,35]. However, these results may have limitations due to the scope and accuracy of the testing. Smaller particles may not have been recovered, and plastic particles at the submicron (0.2 μm) or micron (2.0 μm) levels can penetrate plant roots and enter various above-ground organs [56]. From the current findings, animal-derived ingredients processed from offal or other by-products pose a greater risk of contamination, while the limitations of analytical techniques present a significant challenge to safety assessments.

4.1.3. Other high-nutritional-value feed proteins

The emerging research direction in aquafeed involves utilizing recyclable biological components (such as waste streams, industrial by-products, food waste, and seawater) as culture media for cultivating high-nutritional-value feed proteins, including insects, microbial unicellular organisms, and seaweed [57]. However, these recycled media may accumulate a large number of MPs. For example, despite extensive efforts in waste separation, significant amounts of plastics, predominantly polyethylene (PE), polypropylene (PP), and polystyrene (PS) from food packaging, persist in compost, digestate, and food waste [58]. Insects, a popular research subject in this field, can be rapidly cultivated using food waste as a culture medium [59]. Research indicated that black soldier flies ingested MPs with minimal bioaccumulation or were mostly eliminated [60]. In addition, a survey conducted along the eastern coast of China found that the average abundance of MPs in five species of large algae reached 1243.0 ± 1394.0 items/kg [61]. It is evident that there is a high risk of MPs accumulation in recycled biological resources.

4.2. Packaging materials

For cost-effectiveness and practicality, feed bags are typically made of single-layer plastic composed of PE and PP [62]. During transportation, these bags are often damaged, resulting in the generation of tiny plastic particles [62]. These fragments can mix into the feed ingredients and subsequently be compressed together to form aquafeed pellets. Through analyzing the MPs extracted from aquafeeds, Siddique et al. proposed that the multicolored MPs could originate from colored packaging materials like ropes or feed bags [8]. In addition, plasticizers in the packaging bags (such as short-chain chlorinated paraffins and medium-chain chlorinated paraffins) may gradually migrate into the feed, depending on storage temperature and time [63]. Plasticizers, industrial chemicals employed to enhance material plasticity, flexibility, and durability, possess toxicity to humans through ingestion, inhalation, or dermal contact [64]. A survey revealed that all tested samples of pig feed contained plasticizers, including dibutyl phthalate (DBP) and bis (2-ethylhexyl) phthalate (DEHP) [65]. Wang et al. observed bisphenol compounds (BPs) averaging 1179 ng/g in a survey of 30 feed bag samples [66]. Xu et al. found a significant positive correlation between DEHP and PET MPs in animal feed, indicating that they are homologous, mainly from processing and packaging materials [65].

4.3. Production and processing

The production of aquafeeds encompasses several sequential processes including conveying, crushing, sieving, and mixing, followed by extrusion and pelletizing under high temperature and pressure conditions, and finally cooling and packaging [67]. Aquafeed ingredients typically require a high degree of crushing [68], such as the ingredients for large yellow croaker (*Pseudosciaena crocea*) feed being required to pass through a sieve with apertures of 200–250 μm [69]. After the crushing and sieving processes, MPs from both ingredients and the environment become finer in size and larger in quantity. In the production of expanded aquafeeds, the prepared feed mixture undergoes extrusion under high temperatures (120–130 °C) and pressures (20–30 bar) [70]. However, elevated temperatures can lead to the release of considerable amounts of micro- and nano-plastics from plastic packaging/containers. Liu et al. confirmed that various types of plastic products released millions of submicron and micron-sized plastic particles at 100 °C [71]. Plastic polymers, subject to thermal degradation or chain degradation, undergo fragmentation into smaller fragments and monomers [72].

5. Effects of MPs ingestion on health and growth of aquatic organisms

Ingestion of plastics by aquatic animals is common in natural waters as those small MPs are easily mistaken for food and swallowed. The frequency of accidental ingestion depends on the biology of the aquatic animal, such as feeding frequency, foraging preferences and body size [73], as well as on the environmental concentration of MPs in the organisms [74]. Nevertheless, this “accidental ingestion” may be inevitable for aquaculture animals, since the contaminated aquafeed stands as the primary food source and the MPs have been firmly immobilized in the feed particles (Fig. 2).

5.1. Health risks and physiological effects

The MPs can persist in the digestive tracts of aquatic organisms for days to weeks, posing a significant threat to their health [75]. In severe cases, MPs can obstruct the intestines, resulting in growth retardation or even mortality [76]. Small zooplankton, particularly in their juvenile stages, appear more susceptible to these negative effects [77]. Despite not often causing acute fish mortality, MPs ingestion frequently leads to an array of adverse consequences [27]. Qiao et al. observed no zebrafish mortality following 21-day MPs exposure, yet significant histopathological damage to the intestinal tract was evident, particularly in fish exposed to fibers [78]. Additionally, MPs increased intestinal permeability in fish, elevating the risk of inflammation [78]. Moreover, MPs can disrupt the normal physiological and immune functions of fish by altering their intestinal flora [22]. The physical damage caused by MPs or substances adhering to their surfaces has been proposed as the reason for intestinal flora disruption in fish [79]. Notably, smaller-sized MPs particles have shown greater harm to the intestinal tissues of aquatic animals [80]. Sayed et al. demonstrated histological damage to the

Table 3
Occurrence and characteristics of the MP in FM.

Origin	Raw material	Abundance	Shape	Colour	Categories	References
Malaysia	*Rastrelliger kanagurta* *Rastrelliger kanagurta* *Rastrelliger kanagurta* (gastrointestinal tract, scales, fish head and bone)	327.27 MP/kg	Fragments (78.2 %), Filaments (13.4 %), films (8.4 %)	–	PE (63.0 %), PP (27.8 %), PET (8.8 %), NY6 (0.4 %)	[36]
Iran	*Oncorhynchus* spp *Sardine* spp *Sardine* spp *Clupeonella* spp	188.33 MP/kg	Fragments (67 %), films (19 %), pellet (8 %), fiber (6 %)	–	PP (45 %), PS (24 %), PE (19 %), PET (8 %), rayon (4 %)	[35]
South Africa	*Sardinops sagax*	186.7 ± 17.6 MP/kg	Fragments (52.6 %), fiber/filament (38.7 %), film (8.5 %), foam (0.2 %)	Transparent (30.7 %), green (19.4 %), blue (15.6 %), white (10.7 %), black (8.1 %)	PE (30.3 %), PP (25.4 %), acrylic acid (9 %), PET (5.7 %)	[37]
Norway	*Micromesistus poutassou*	33.3 ± 6.7 MP/kg				
Denmark	*Ammodytes* spp, *Engrailus engrasicolus*, *Clupea harengus*, *Micromesistus poutassou*	68.0 ± 35.3 MP/kg				
	Ammodytes spp, *Engrailus engrasicolus*, *Clupea harengus*, *Micromesistus poutassou*, *Sardina pilchardus*, *Sprattus*	70.0 ± 26.7 MP/kg				
	–	74.0 ± 13.3 MP/kg				
Morocco	*Sardina pilcardus*, *Sardinella aurita*, *Scomber japonicas*	293.3 ± 54.6 MP/kg				
	–	213.3 ± 69.6 MP/kg				
China	*Engrailus japonicus.*, *Sardinops* spp	413.3 ± 113.9 MP/kg				
	Engrailus japonicus., *Sardinops* spp	313.3 ± 63.6 MP/kg				
	Engrailus japonicus.	466.7 ± 40.6 MP/kg				
	Engrailus japonicus.	526.7 ± 100.9 MP/kg				
	Engrailus japonicus.	400.0 ± 41.6 MP/kg				
	Engrailus japonicus.	153.3 ± 57.0 MP/kg				
	Engrailus japonicus., *Sardinops* spp	113.3 ± 6.7/MPs/kg				
	Engrailus japonicus., *Sardinops* spp	313.3 ± 46.7 MP/kg				
Chili	–	53.3 ± 17.6 MP/kg				
Peru	–	66.7 ± 29.1 MP/kg				
	Engraulis ringens	60.0 ± 11.5 MP/kg				
	Engraulis ringens	46.7 ± 6.7 MP/kg				
Mauritania	–	80.0 ± 40.0 MP/kg				
Turkey	*Engrailus engrasicolus*, *Sprattus*	40.0 ± 11.5 MP/kg				
India	*Sardinops* spp., *Carangidae*	106 ± 29.1 MP/kg				
	Balistidae, *Trichiurus lepturus*, *Sebastidae*, *Carangidae*, *Synodontidae*, *Sardinella longiceps*	373.3 ± 81.1 MP/kg				
	Balistidae, *Trichiurus lepturus*, *Sebastidae*, *Carangidae*, *Synodontidae*, *Sardinella longiceps*	100.0 ± 41.6 MP/kg				
Denmark	Ammodytes spp., *Engrailus engrasicolus*, *Clupea harengus*, *Micromesistus poutassou*, *Sardina pilchardus*, *Sprattus*	33.3 ± 6.7 MP/kg				
Chile	*Engraulis mordax*, *Cirrhinus molitorella*	2.0 ± 0.4 MP/g	Fibers (96.1 %), fragments (3.0 %), films (0.6 %), pellets (0.3 %)	–	CP (66.2 %), PP (7.5 %), PET (7.3 %), PE (5.6 %), PS (3.1 %), PA (1.7 %)	[10]
China	*Engraulis japonicus*, Trash fish	15.9 ± 2.7 MP/g				
Denmark	*Hypophthalmichthys nobilis*, *Ammodytes personatus*, *Brevoortia*	1.5 ± 0.3 MP/g				
Mauritania	*Sardina pilchardus*	1.6 ± 0.7 MP/g				
Mexico	*Sardinops sagax*, *Scomber japonicus*, *Engraulis mordax*, *Cetengraulis mysticetus*, *Etrumeus teres*, *Trachurus symmetricus*	1.4 ± 0.5 MP/g				

(continued on next page)

Table 3 (*continued*)

Origin	Raw material	Abundance	Shape	Colour	Categories	References
Myanmar	*Sardinops sagax*, Trash fish	17.3 ± 2.8 MP/g				
Panama	*Sardinops sagax*, *Clupea pallasi*	2.6 ± 0.4 MP/g				
Peru	*Engraulis mordax*	7.3 ± 1.9 MP/g				
Russia	*Theragra chalcogramma*, *Pleuronectiformes*, *Gadus macrocephalus*	1.9 ± 0.4 MP/g				
USA	*Clupea pallasi*, *Gadus macrocephalus*	3.1 ± 0.6 MP/g				
Norway	*Clupea harengus*	2.00 APs/g	Fibres (82.5 %), fragments (16.8 %), films (0.8 %)	Blue (70 %), red (11.8 %), black (6.5 %)	PA, PET, PE, PP and PS	[9]
Norway	*Clupea harengus*	1.07 APs/g				
UK	*Coregoninae* spp., *Oncorhynchus* spp. (trimmings)	1.43 APs/g				
UK	*Coregoninae* spp., *Oncorhynchus* spp. (trimmings)	1.10 APs/g				
UK	*Coregoninae* spp., fish trimmings	1.30 APs/g				
Scotland	*Coregoninae* spp	1.47 APs/g				
South America	*Sardina* spp., *Engraulis* spp	1.27 APs/g				
Unknown	Dried whole squid	1.13 APs/g				
Antarctic krill	*Euphausia superba*	1.33 APs/g				
China	–	54 0.0 MP/kg	Film (69.39 %) fiber (23.47 %), fragment (7.14 %)	Transparent (50 %), blue (14.29 %), green (11.22 %), white (10.2 %), yellow (8.16 %)	Paraffin (45.9 %), PE (24.5 %)	[38]
Peru	–	20.0 MP/kg				
Denmark	–	30.0 MP/kg				
Russia	–	50.0 MP/kg				
Thailand	–	10.0 MP/kg				
–	*Coregoninae* spp	123.9 ± 16.5 MP/kg	–	Blue, white, red, black, orange	–	[34]

Note: PE, polyethylene; NY6, Nylon 6; CP, Cellophane; PP, polypropylene; PET, polyethylene terephthalate; PS, polystyrene; PA, polyamide; APs, anthropogenic particles.

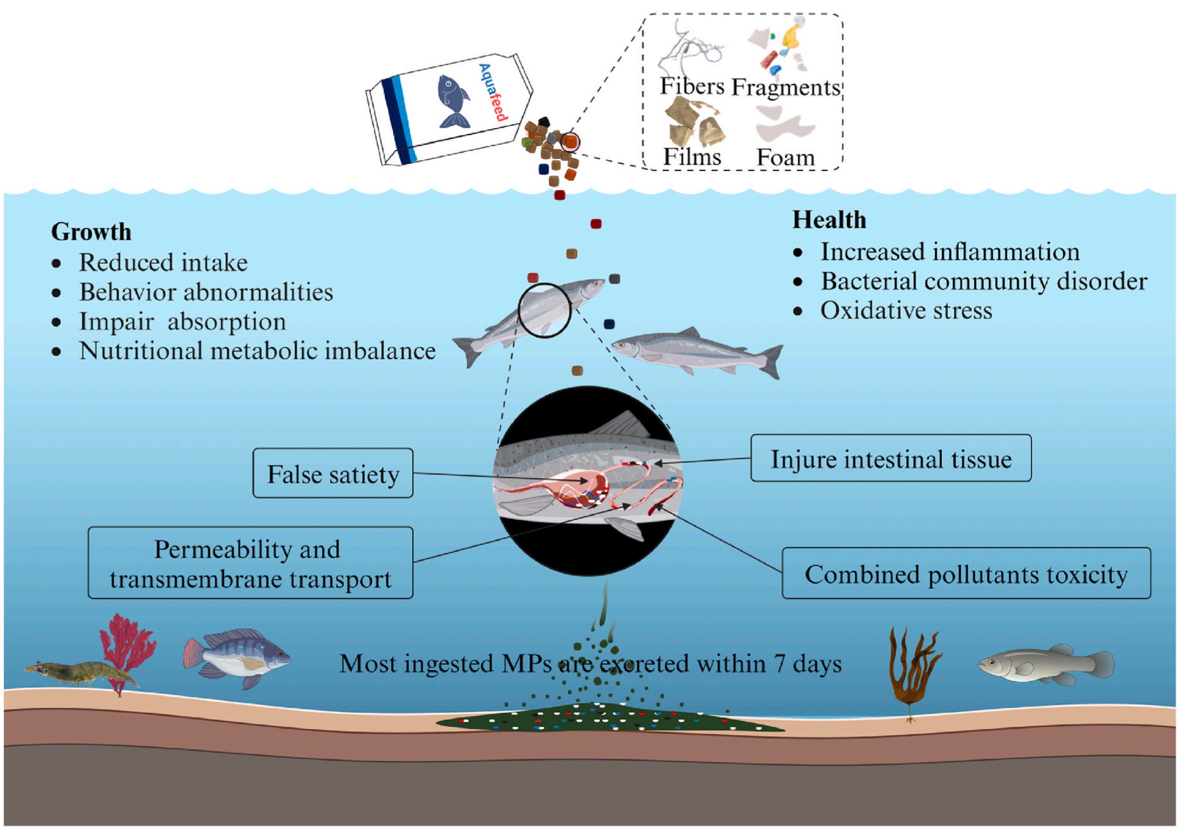

Fig. 2. Effects of MPs ingestion on aquatic animal growth and health.

kidney, liver, and intestine of fish upon ingesting plastic particles as small as nanometers [81].

Concerningly, plasticizers, chlorinated paraffins, and bisphenol compounds can migrate into animal feed during processing and packaging, known for their various toxicities including carcinogenicity and neurotoxicity [64]. These chemicals, released from ingested MPs, pose additional threats to fish health [76]. Previous studies have demonstrated the transfer of polybrominated diphenyl ethers (PBDEs) from plastics to the tissues of organisms [82], with a subsequent correlation identified between fish tissue PBDE levels and environmental plastic particle abundance [83]. MPs also act as carriers of organic pollutants and heavy metals [84]. Combined exposure to MPs and arsenic induced more severe oxidative stress and metabolic disorders in zebrafish compared to exposure to MPs alone [85]. This suggests that while MPs can cause harm to animals and humans, the adsorbed contaminants may pose even greater risks.

5.2. Effects on growth of aquatic organisms

Numerous studies have documented growth inhibition in various aquatic organisms, including fish, mollusks, and crustaceans, when exposed to MPs [22–25]. Ingestion of foods containing MPs may induce false satiety in fish, altering their feeding behaviors and potentially affecting growth rates and overall health [76]. Notably, Welden and Cowie observed prolonged retention of MPs in *Nephrops norvegicus*, resulting in reduced food intake [25]. Moreover, ingested MPs can disrupt nutrient absorption by influencing intestinal permeability and transmembrane transport functions [86], as well as induce imbalances in intestinal flora, affecting nutrient metabolism in animals [87].

The impacts of ingested MPs on aquatic organisms may hinge on their duration in the gastrointestinal tract. Some studies suggest limited effects of MPs ingestion on aquatic animal growth, evidence exists indicating that ingested MPs can be excreted relatively quickly, allowing affected organisms to recover [26,88]. The excretion efficiency seems to be correlated with the size of MPs, with smaller particles exhibiting higher excretion rates [88]. Additionally, the shape of MPs also influences the excretion rate, with fibers exhibiting lower excretion rates compared to fragments and films [89]. Given that aquafeeds often contain MPs fibers and fragments, these shapes may prolong retention in the digestive tracts of farmed animals. Moreover, longer exposure periods to MPs have been linked to more severe damage in test animals [25]. As aquaculture production cycles typically span from one to several years, the sustained presence of MPs holds the potential to adversely impact the growth of farmed animals over extended durations.

6. Risk of MPs contamination in aquatic products

The transport of MPs from the environment to the human food chain has long been a public concern (Fig. 3). A report encompassing the last decade of research revealed MPs contamination in 926 seafood species, spanning finfish, crustaceans, molluscs and seaweeds, demonstrating aquatic products are the potential transmission route for MPs [90]. Researchers Clark et al. have confirmed that plastic particles ingested by fish through dietary intake can traverse the intestinal barrier and enter the bloodstream, leading to systemic distribution, including in edible tissues [91]. Epidemiological studies have indicated a higher prevalence of related diseases in certain populations exposed to MPs [92]. Recently, anionic nano-plastics have been shown to precipitate the formation and propagation of α-synuclein protein fibrils, which may increase the risk of Parkinson's disease [93]. Additionally, MPs and heavy metals (Cd, Cr, Cu and Pb) in aquatic animals have been shown to correlate, further emphasizing the risk [94].

In nature, the accumulation of MPs in aquatic animals depends mainly on their mobility and ecological characteristics. Within the same species, less active animals accumulate more MPs. For example, Capparelli et al. found that 50 % more MPs were detected in the hermit crab *Menippe mercenaria* compared to the free-swimming *Callinectes sapidus* [95]. In addition, benthic populations also accumulate more MPs, e.g.,

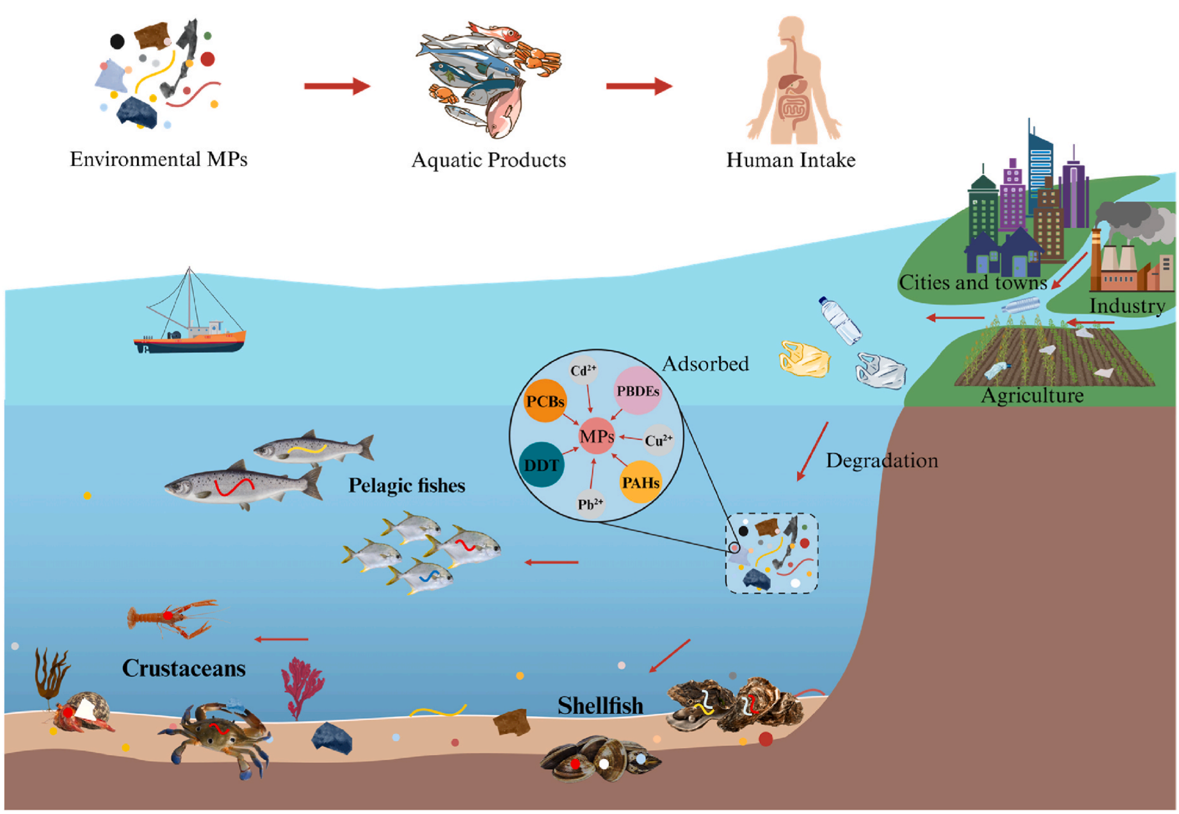

Fig. 3. Risk of MPs contamination in aquatic foods.

Sultan et al. have detected much higher concentrations of MPs in the bottom-feeding *Pseudapocryptes elongatus* compared to other fish [96]. As for different species, the degree of accumulation of MPs depends on the differences in their feeding habits, nutritional levels and habitats [28]. Studies have demonstrated that benthic crustaceans such as shrimps and crabs and filter-feeding shellfish tend to accumulate more MPs than pelagically active species [28]. More worryingly, unlike fish and crustaceans, humans typically consume all the soft parts of shellfish, including the gastrointestinal tract and gills where MPs tend to accumulate. Hence, the contamination of aquatic products, especially their edible parts, with MPs should be emphasized to assess the risk of consumption.

Although seafood consumption patterns vary based on the development and dietary habits of each country and region, aquatic products serve as a vital food source for humans. Surveys showed that seafood from Asia accounted for the largest proportion (47.91 %) of contaminated species globally, while those from Antarctica accounted for the smallest proportion (0.12 %) [90], reflecting the significant geographic variation in the abundance of MPs in aquatic products. According to a report estimating the daily intake of seafood recommended for humans (27.40–37.82 g, depending on age and gender) and the average MPs concentration in seafood (1.48 MP/g), the daily ingestion of MPs through seafood consumption is estimated to range from 40.55 to 55.97 MPs [97].

7. Strategies for mitigating MPs contamination in aquafeeds

Mitigating the presence of MPs in aquafeeds represents a significant challenge yet a crucial endeavor amid global MPs contamination. For specific sources of pollution, a series of measures are targeted here (Fig. 4). Regarding feed ingredients, reducing the usage of FM is paramount due to its high contamination rate [57], aligning with the ongoing trend in aquafeed development. Instead, greater emphasis should be placed on plant-based ingredients, supported by current evidence suggesting their lower contamination levels and wide availability [35]. While promoting the utilization of recycled biological resources (inclusive of animal by-products and those derived from waste streams), stringent control over the sourcing and safety of these products is imperative.

Addressing post-harvest contamination in ingredients involves focusing on feed packaging and production practices as primary sources [8]. Using reusable, abrasion-resistant cotton and plastic bags for feed packaging is recommended, considering the stability and potential toxicity of polymers [98]. To curb the production and migration of MPs, transportation of feeds and ingredients should minimize mechanical friction, while storage should avoid prolonged periods at high temperatures. Pre-separation of foreign materials before crushing and sieving feed ingredients is advised to prevent their breakdown into smaller MP-sized particles. In all stages of feed production, minimizing the use of plastic appliances and equipment is essential. Moreover, replacing expanded feeds with regular feeds that are produced under milder (extruded) conditions will likely help to reduce the number of MPs and the release of other toxins in the feed.

Implementing the recommendations proposed by Xu et al. [65] to streamline production chains can further aid in controlling MPs contamination in aquafeeds. For instance, reducing the types of ingredients will help to reduce the processing stages such as crushing, screening and extrusion. These measures require robust support and assistance from governments, institutions, and the enactment of stringent regulations to reinforce monitoring efforts. Collaboration among stakeholders is crucial to overcome these hurdles and institute effective changes for the reduction of MPs contamination in aquafeeds.

8. Conclusions and perspectives

In summary, this review emphasizes the significant and potential hazards of MPs contamination in aquafeeds. Through a comprehensive analysis of current research, we have revealed the widespread presence of MPs in aquafeeds, along with their diverse characteristics and multifaceted sources. Analytical methods play a pivotal role in the study

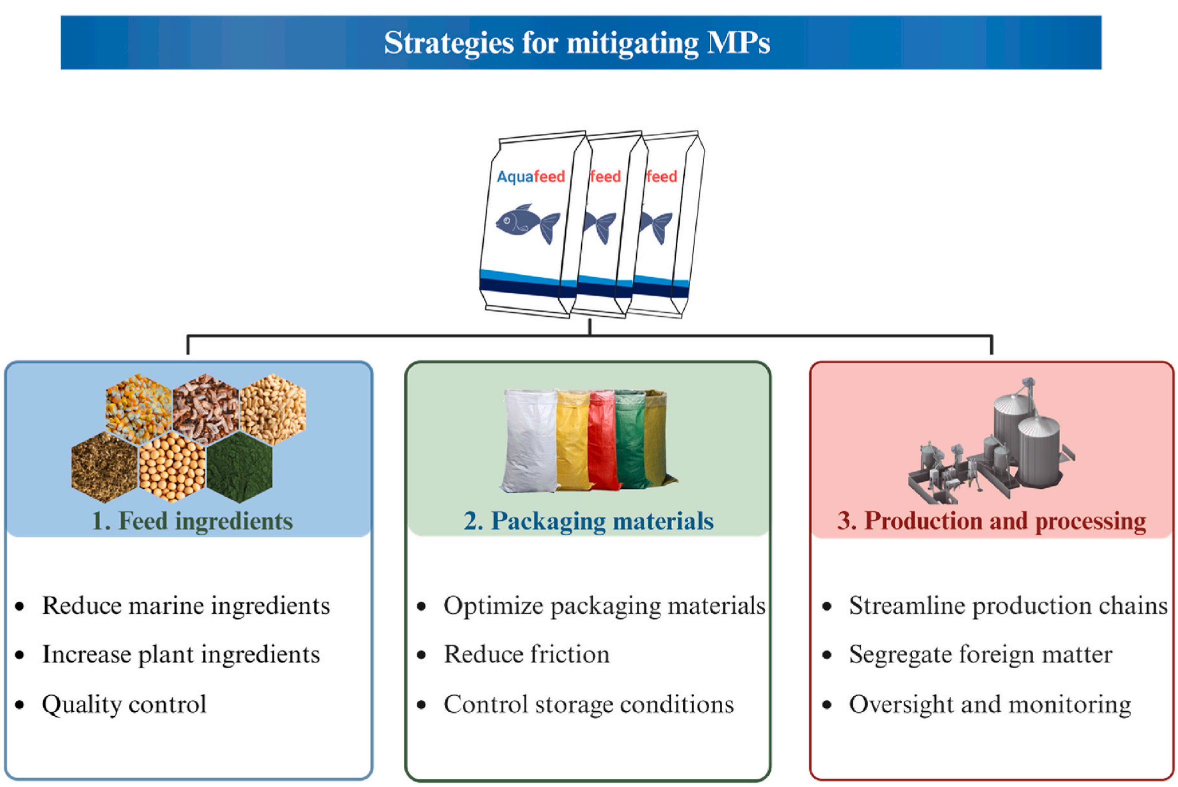

Fig. 4. Strategies to mitigate contamination of MPs in aquafeeds.

of MPs, offering insights into the abundance, types, and potential health risks of contamination in samples. The study underscores the urgent need for tailored analytical methods specifically designed for the complex composition of aquafeeds to ensure the accurate detection and quantification of MPs. Standardized protocols for sample preparation, digestion, and characterization are crucial for promoting comparability and reliability across studies. Furthermore, this research contributes to a deeper understanding of the long-term impacts of MPs pollution on aquatic organisms and human food safety. Clearly, mitigating MPs pollution in aquafeeds is imperative. It is a complex task that requires the collective efforts and sustained attention of all stakeholders to address this global challenge.

CRediT authorship contribution statement

Zeliang Su: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Liangfu Wei:** Validation, Software, Resources, Methodology, Investigation. **Linyong Zhi:** Formal analysis, Software. **Xiaomei Huang:** Validation, Software, Resources, Data curation. **Xu Wang:** Writing – review & editing, Software, Resources. **Jun Wang:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Data curation.

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

Data will be made available on request.

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