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Review

Addressing Phosphorus Waste in Open Flow Freshwater Fish Farms: Challenges and Solutions

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Abstract: Legislation and interest exists to protect and restore freshwater and marine ecosystems from the environmental impact of aquaculture. However, aquaculture-induced eutrophication remains a major environmental concern. Water soluble phosphorus, uneaten feed, feces, and metabolic waste from farmed fish increase phosphorus concentrations in adjacent waters. In open freshwater fish farms, in particular, the effects can be more immediate, as excess phosphorus is introduced directly into ecosystems. Several intestinal enzymes, transporters, and regulating factors have been implicated in farmed fish dietary phosphorus retention. For example, alkaline phosphatase and other transporters aid in the absorption of phosphorus in the anterior intestine, while pH, calcium, and vitamin D influence these enzymes and transporters. This process may also be influenced by intestinal morphology and the gut microbiome. To reduce phosphorus pollution from open flow fish farms, a thorough understanding of the processes that affect nutrient retention and absorption, as well as the impact of dietary factors, anti-nutritional substances, and intestinal morphology, is required. Aquaculture can be made more sustainable by reducing phosphorus release. This can be achieved by optimizing feed composition, adding functional feed ingredients, managing gut health, and treating effluent aquaculture waters with bioremediation and absorbing materials. Anti-nutritional factors can be mitigated through processing and through the use of functional feed additives. Addressing these issues will reduce aquaculture's environmental impact, ensuring aquatic ecosystem health and global food security. In addition, treating effluent aquaculture waters with bioremediation and absorbing materials can remove phosphorus from the water, preventing it from entering the environment. This can further reduce the environmental impact of aquaculture and help to ensure the sustainability of this sector.

Keywords: aquaculture nutrition; phosphorus pollution; sustainability; eutrophication

Key Contribution: This review highlights the importance of understanding the mechanisms that affect phosphorus retention and absorption in farmed fish. This understanding is essential for developing strategies to reduce phosphorus pollution from open-flow fish farms and improve aquaculture sustainability.

Citation: Nathanailides, C.; Kolygas, M.; Tsoumani, M.; Gouva, E.; Mavraganis, T.; Karayanni, H. Addressing Phosphorus Waste in Open Flow Freshwater Fish Farms: Challenges and Solutions. *Fishes* **2023**, *8*, 442. https://doi.org/10.3390/fishes8090442

Academic Editor: Ewen McLean

Received: 9 August 2023
Accepted: 25 August 2023
Published: 31 August 2023

1. Introduction

Aquaculture, like other forms of agriculture, has environmental impacts. Farmed fish release nitrogen and phosphorus, which, if left untreated in water effluents, enter surface water bodies and cause eutrophication. Fresh water fish farms may also discharge veterinary drugs and antibiotics, harming aquatic biodiversity, causing the accumulation of antibiotics, and increasing antibiotic resistance [1–3].

Aquaculture has experienced rapid growth throughout history, driven by the increasing demand for seafood and the over-exploitation of fish stocks. As the industry strives to address food security concerns, fish nutrition plays a vital role in ensuring the sustainability of the sector. To achieve this, researchers are exploring new feed compositions and ingredients that can optimize fish health and performance. Phosphorus holds a dual significance in fish nutrition. Firstly, it is an essential ingredient in fish feeds, since it is required for various physiological processes, including bone formation, energy metabolism, and cellular functions. Adequate phosphorus levels in fish diets are crucial for promoting growth and overall well-being [4–6]. However, phosphorus also presents a potential challenge in terms of environmental pollution. Excessive phosphorus discharge from aquaculture operations can lead to water eutrophication, algal blooms, and other negative impacts on aquatic ecosystems. Phosphorus runoff from fish farms contributes to the nutrient load in surrounding water bodies, which can have detrimental effects on water quality and biodiversity [7,8]. To mitigate these environmental concerns, aquaculture endeavours to optimize phosphorus utilization and minimize its environmental footprint. This involves developing innovative feed formulations that enhance phosphorus digestibility and absorption in farmed fish, thereby reducing phosphorus excretion into the environment [9]. Additionally, techniques such as precision feeding, which aim to match feed supply with the nutritional requirements of fish, help prevent excessive phosphorus discharge [10]. By addressing the dual role of phosphorus as an essential ingredient and a potential parameter of pollution, the aquaculture industry can achieve sustainable growth while minimizing its environmental impact. The efficiency of phosphorus retention or absorption in the fish intestine can be influenced by a complex interplay of dietary, anatomical, and physiological factors. As shown in Figure 1, various factors are implicated in the waste of phosphorus generated by farmed fish. Anatomical and physiological parameters, including active transporters, intestinal alkaline phosphatases, and the anatomy and density of microvilli and intestinal folds, play essential roles in determining the efficiency of dietary phosphorus absorption and consequently, the amount of phosphorus wasted by farmed fish [11–15].

Research advancements have identified ways to improve these parameters and reduce phosphorus waste. Improved nutrient utilization, including phosphorus retention, can be achieved through the use of probiotics, which directly or indirectly enhance intestinal phosphorus absorption. Probiotics exert their positive effects on phosphorus absorption in fish by modulating gut health and competing with harmful bacteria [16–18]. By influencing the composition and balance of the gut microbiota, probiotics create a favorable environment for nutrient, including phosphorus, digestion and absorption [19–22]. This leads to improved functionality of the intestinal epithelium and enhanced nutrient transport mechanisms, including active transporters responsible for phosphorus uptake [23,24]. Moreover, probiotics outcompete pathogenic bacteria for nutrients and adhesion sites in the fish gut, reducing their presence and maintaining a healthier gut environment [25]. This competitive exclusion contributes to optimal nutrient, including phosphorus, absorption, which can positively impact phosphorus waste in farmed fish. As a result, probiotics not only improve the efficiency of dietary phosphorus absorption by enhancing various anatomical and physiological parameters but also indirectly reduce the waste of phosphorus in farmed fish [23]. By promoting gut health and mitigating the negative influence of harmful bacteria, probiotics contribute to improved intestinal phosphorus absorption and subsequently help reduce the environmental impact of phosphorus waste in aquaculture systems [17,26].

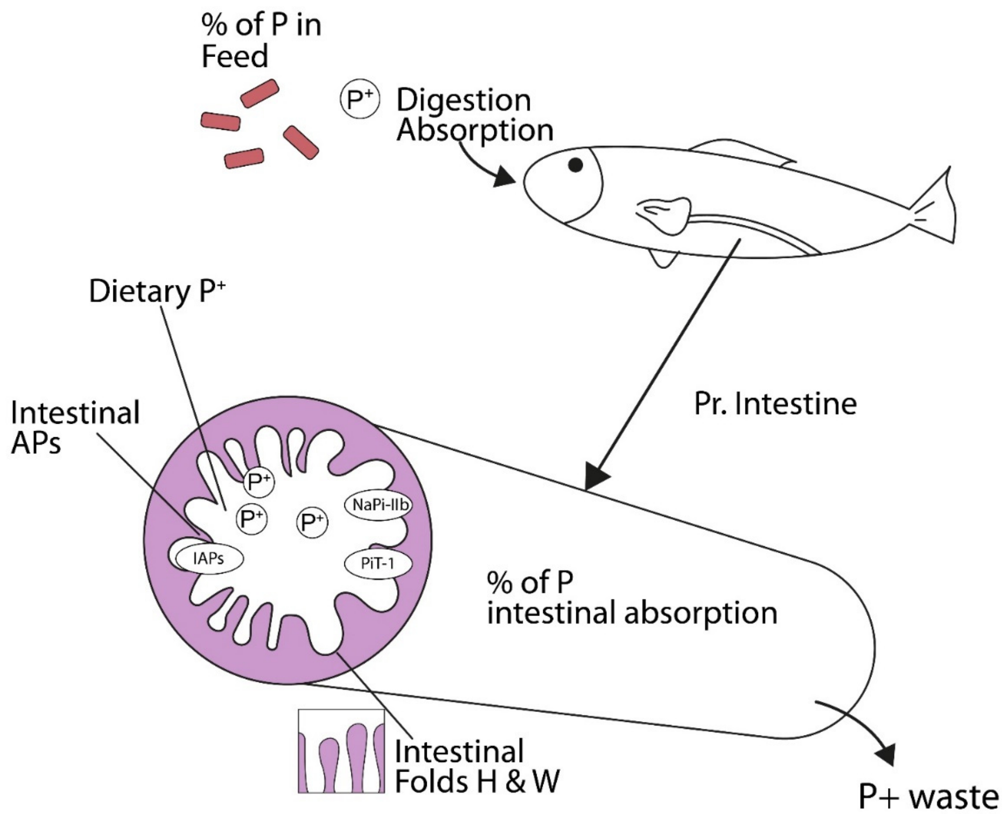

Figure 1. Gut microbiome (epithelium, mucus layer), active transporters (e.g., PiT-1, NaPi-IIb), intestinal alkaline phosphatases (IAPs), and intestinal fold morphology (height and width) are implicated in the efficiency of dietary phosphorus (P+) absorption in the proximal intestinal segment (pr. intestine), affecting the waste of P in farmed fish.

1.1. *Phosphorus Requirements of Fish Farmed in Open Flow Aquaculture Systems*

Phosphorus is an essential nutrient for fish, playing a crucial role in various physiological functions, including bone formation, tissue growth, acid–base balance, energy metabolism, and reproduction. The phosphorus requirements of fish depend on several factors, such as species, life stage, growth rate, and water temperature [6,27,28]. Higher phosphorus requirements are associated with growth and skeletal development [5,29,30], and this is particularly interesting for farmed fish. Salmonids and other carnivorous fish species are widely cultivated in open flow aquaculture systems, and they require high levels of protein in their diets. The protein requirement varies depending on the size and life stage of the fish, but generally ranges from 32–45% of the diet. The phosphorus content of salmonids may vary depending on diets composition, but in Europe, it typically ranges from 0.7–1.4% [31,32].

1.2. *The Environmental Impact of Aquaculture, with Emphasis on Open Flow Fish Farms*

Intensive aquaculture is frequently based on open flow fish farms [33–35], which must quickly release the water outflow into neighboring rivers, allowing only limited time for water treatment and resulting in phosphorus release downstream [8,36]. In most freshwater ecosystems, phosphorus (P) is the limiting nutrient, whereas nitrogen (N) is the limiting nutrient in marine ecosystems. As a result, monitoring anthropogenic sources of phosphorus in freshwater ecosystems is a useful tool for determining the causes of eutrophication and its environmental impact. One possible source for phosphorus in rivers and lakes is aquaculture feed. However, farmed fish require phosphorus in their diet. Diets lacking in phosphorus can lead to severe pathological problems in farmed fish [37–39]. Phosphorus-containing fish feeds can contribute to aquatic pollution by releasing uneaten feed, feces, and metabolic wastes of farmed fish [40].

There is uncertainty regarding the range of potential ecological parameters affected by phosphorus pollution in aquatic ecosystems; however, fish farm effluents can account for most of the downstream river eutrophication [41], with ecological effects, such as loss of biodiversity according to nutrient load and mainly via increased levels of phosphorus [42]. The ecological effect of fish farms is evaluated by monitoring the levels of phosphorus they produce, expressed in kilograms of phosphorus produced by fish farms per metric ton of fish produced. The phosphorus load generated can be estimated with direct measurements of water samples, by using fish production and feed records, or by calculating the feed conversion ratio (FCR) combined with chemical analyses of feed and fish [43]. Overall, the increased efficiency of phosphorus absorption can lead to a decrease in the amount of phosphorus wasted in both soluble and solid forms [44].

2. Morphological, Physiological, and Dietary Factors Affecting Phosphorous Absorption in Fish

2.1. Intestinal Morphology and Physiological Mechanisms

Fish intestine morphometric characteristics, including the surface area, as well as the presence of specialized cells, can reveal an intriguing relationship between anatomy and nutrient absorption efficiency [45–47]. Fish possess a multitude of intestinal folds within their intestinal lining, and these fulfill a similar function to that of the mammalian intestinal villi, in that they augment the surface area available for nutrient absorption. In the pertinent academic literature, to depict the anatomical structure of the intestine in fish, the aforementioned folds are referred to as intestinal folds or intestinal villi. In this current review, the term "intestinal folds" will be employed to designate the folds that bear resemblance to the villi found in the gastrointestinal tract of mammals, specifically within the gut of fish.

The intestinal phosphorus absorption process in fish can be divided into two main phases: luminal and brush-border absorption. Luminal absorption involves the uptake of phosphorus from the intestinal lumen into the enterocytes, while brush-border absorption involves the transport of phosphorus across the brush-border membrane of enterocytes and into the bloodstream [47–49]. Several nutritional experiments have demonstrated the length of intestinal folds and the number of goblet cells to be indicators of feed utilization efficiency [50–52]. Rainbow trout (*Oncorhynchus mykiss*) with higher phosphorus retention efficiencies exhibit longer intestinal folds and higher goblet cell densities compared to those with lower phosphorus retention efficiency [51]. Similarly, studies on Nile tilapia (*Oreochromis niloticus*) have explored the effects of dietary phosphorus levels on intestinal folds morphology and nutrient retention. The digestibility of protein and phosphorous was associated with intestinal fold length [53]. In fact, a complex interplay of transporters, enzymes, and hormones facilitates the process of phosphorous absorption. Thus, the anterior part of the intestine is considered as the primary site of dietary phosphorus absorption, since it exhibits a higher concentration of alkaline phosphatase, an enzyme responsible for phosphate ester hydrolysis, as well as other phosphorus transporters [13,54]. Several transporters and channels have been identified as playing key roles in intestinal phosphorus absorption in fish. These include sodium-dependent phosphate transporters (NaPi-IIb), which are responsible for the luminal uptake of phosphorus, and type III sodium-dependent phosphate transporters (Pit-1), which mediate brush-border uptake [55,56]. Additionally, calcium-sensing receptor (CaSR), transient receptor potential vanilloid 6 (TRPV6), and plasma membrane calcium ATPase (PMCA) are other transporters involved in regulating phosphorus absorption in fish [13].

Regarding vitamins, cholecalciferol, also known as vitamin D3, is a type of fat-soluble vitamin that plays a crucial role in calcium and phosphate metabolism. Cholecalciferol converted into its active form, calcitriol, regulates the absorption of calcium and phosphate in the intestine and influences their levels in the blood. In the context of trout and other farmed fish, cholecalciferol supplementation has been studied for its effects on plasma phosphate levels and phosphorus utilization, and the results indicate that cholecalciferol supplementation can modulate plasma phosphate concentrations, affecting the overall phosphorus balance in fish [57].

Intestinal phosphorus absorption in fish can also be affected by Na^+ [54,58] and hormones such as calcitriol, parathyroid hormone, and fibroblast growth factor [23]. Calcitriol stimulates the expression of NaPi-IIb and Pit-1 transporters, while the parathyroid hormone inhibits NaPi-IIb expression and stimulates PMCA expression. Fibroblast growth factor 23 inhibits calcitriol production and promotes phosphorus excretion in urine.

2.2. Relationship between Fish Gut Structure and Feed Conversion Efficiency

The relationship between fish gut structure and feed conversion efficiency (FCE) is crucial in understanding the potential for reducing phosphorus release in aquaculture. FCE plays a vital role in both economic viability and environmental sustainability. It refers to the ability of fish to convert feed into body mass, and improving FCE means that less feed is required to produce the desired amount of fish biomass. This reduction in feed input has the potential to decrease the release of phosphorus-rich waste into the surrounding aquatic environment.

The gut structure of fish, including factors such as the length and surface area of the intestine, the thickness of the intestinal wall, and the presence of intestinal folds and microvilli, can significantly impact the digestion and absorption of nutrients from the feed, ultimately affecting FCE and phosphorus retention efficiency [59]. Studies have shown that fish with a higher gut surface area or longer intestine tend to exhibit higher FCE, indicating their enhanced ability to digest and absorb nutrients from the feed [60,61]

Moreover, the relationship between FCE and phosphorus pollution in aquaculture is crucial. Low FCE is associated with decreased phosphorus retention efficiency in farmed fish, resulting in increased phosphorus excretion into the water [62–68]. Understanding this relationship enables the creation of effective management strategies to reduce phosphorus pollution in aquaculture systems.

2.3. The Role of Fish Feeds in Nutrient Uptake, with Emphasis on Phosphorous

This intricate interplay of transporters and dietary factors reflects the complex nature of nutrient absorption in farmed fish. Phosphorus retention can be influenced by several dietary parameters, such as the raw materials used as protein and phosphorus sources, and the ratio of phosphorus to other minerals, such as calcium [30,63,65–67,69–73]. The development of new fish feed formulations allows aquaculture to tailor the nutritional composition of the feed to meet the specific requirements of different fish species and use alternative protein sources to reduce the reliance of aquaculture on fish meal and fish oil. However, efforts to replace fish meal with plant proteins in fish diets involve challenges related to the impact on the functional integrity of farmed fish intestines [10,64]. Plant natural defense mechanisms, such as protease inhibitors, phytates, glucosinolates, saponins, tannins, lectins, oligosaccharides, and non-starch polysaccharides, can induce intestinal inflammation [74]. This inflammation is linked to changes in gene expression within the intestine, including the absorption of phosphorus. Furthermore, anti-nutritional factors, such as phytate, can affect how efficiently aquacultured species absorb phosphorus. Phytate is a type of phosphorus present in plant-based feed ingredients commonly used in aquaculture diets. However, many aquatic species have a limited ability to digest phytate because they lack the necessary enzyme, called phytase, which is responsible for breaking it down [6]. To mitigate the negative effects of these anti-nutritional factors, fish feed processing methods are employed to neutralize harmful compounds present in plant ingredients and to prevent adverse effects on fish. This includes techniques to destroy or reduce the presence of plant natural defense mechanisms. Phytase, for example, an enzyme that can breakdown phytic acid, is a useful tool that can help fish make the best use of phosphorus available in plant protein-based feeds. Studies have shown that its addition can increase the availability of phosphorus in fish diets, leading to improved growth and health [75–80]. Interestingly, the soybean meal (SBM) commonly used in fish diets has been found to impact nutrient absorption, downregulating the expression of fabp2, a fatty acid-binding protein responsible for lipid absorption in the gut. This disruption in fabp2 expression can interfere with the transport and absorption of lipids, leading to reduced lipid intestinal uptake [81]. Decreased fabp2 expression has been particularly observed in fish experiencing SBM-induced inflammation in the distal portion of the intestine [82,83]. Overall, when fed plant proteins, farmed fish often exhibit intestinal inflammation, which can be addressed by incorporating functional feed additives or employing processing techniques for plant proteins [84,85]. This becomes especially important, given the growing trend of substituting fish meal with plant protein in aquafeed.

The physiological mechanisms involved in intestinal phosphorus absorption in farmed fish are complex and multifaceted, and are influenced by various nutritional and physiological factors such as pH, calcium, and anti-nutritional factors (Figure 2). Understanding these mechanisms is important for optimizing the formulation of fish diets and improving the efficiency and sustainability of aquaculture production.

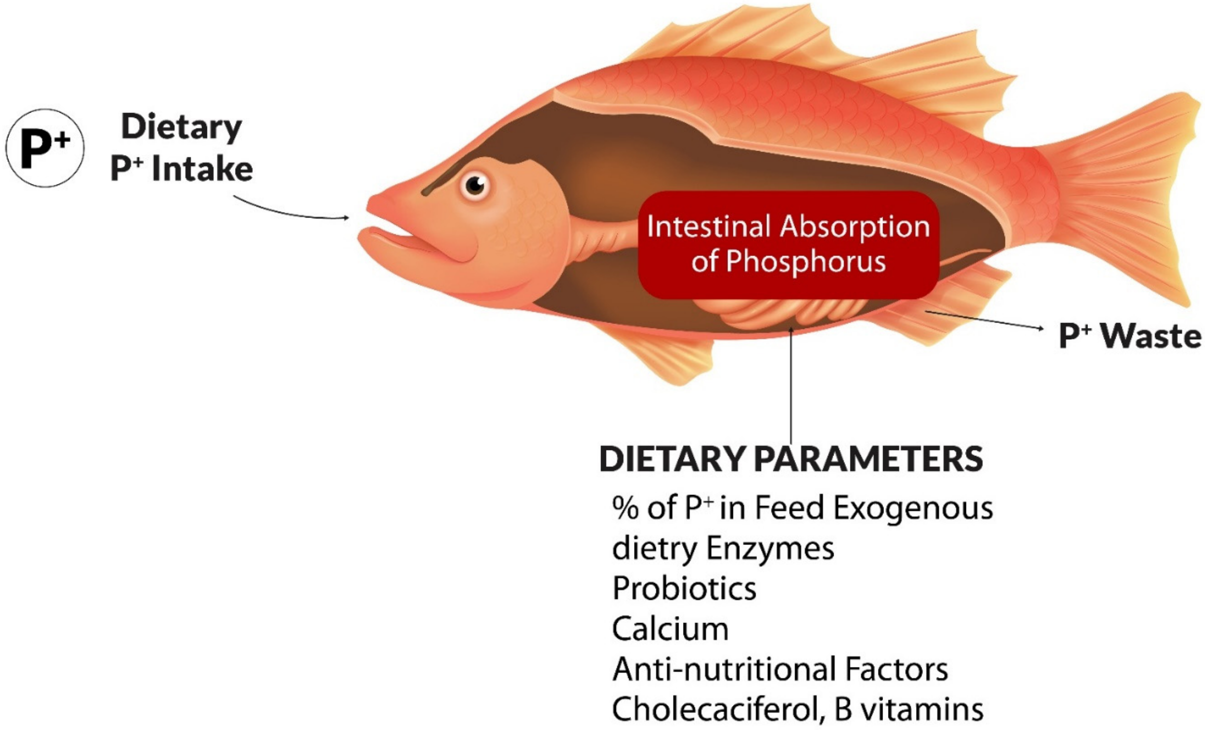

Figure 2. Dietary factors affecting phosphorus waste of farmed fish [20,64,65,67].

Dietary phosphorus levels can also affect phosphorus absorption in farmed fish, influencing the expression of phosphate transporters like NaPi-IIb and Pit-1, with the highest expression observed in the anterior intestine, followed by the posterior and middle intestines [12,86,87]. Increasing the dietary levels of calcium and vitamin D has been shown to enhance phosphorus absorption by upregulating the expression of sodium-phosphate co-transporters in the fish intestine, particularly in the anterior segment [37,55].

2.4. Effect of Probiotics on the Environmental Impact of Freshwater Fish Farms

The utilization of probiotics in aquaculture offers a promising approach for reducing phosphorus pollution and implementing effective nutrient management strategies in fish farm effluents. Probiotics, particularly *Bacillus* strains, have shown the ability to modulate various water quality parameters, including phosphates [26,87]. This is because probiotics utilize phosphates for their own metabolic processes, effectively decreasing the concentration of this nutrient in aquaculture waters [88]. The positive impact of probiotics on reducing orthophosphate concentrations in treated ponds, thereby removing phosphorus, nitrogen, and organic matter from aquaculture systems, illustrates the potential of this method for reducing phosphorus pollution by aquaculture [18,89]. For example, application of commercial probiotics in *Penaeus vannamei* ponds resulted in reduced nitrogen and phosphorus concentrations and increased shrimp yields. Similar findings were reported by Kumar et al. [90,91], who observed a reduction in total NH_4-N, nitrogen, NO_2-N, NO_3-N, and phosphorus concentrations with the use of probiotics.

Probiotic supplementation in fish feed offers several physiological and anatomical benefits that positively impact nutrient absorption, including phosphorus retention. The elongation of intestinal folds, stimulated by probiotics, results in an increased absorptive surface area, thereby enhancing nutrient bioavailability. Specific strains of probiotics can stimulate the elongation of intestinal folds in the midgut and hindgut of fish, as evidenced by a comparison of probiotic-treated groups with control groups [21,92–96]. The production of short-chain fatty acids (SCFAs) by probiotic bacteria further stimulates the production of gastrointestinal peptides, enhancing nutrient absorption capacity and ultimately contributing to improved growth performance [97–99].

In addition to the above, there is emerging evidence that probiotics can have a positive effect on gut health [25] and positively influence enzyme levels through various physiological pathways, ultimately improving fish digestion and nutrient utilization [100]. For example, probiotics may directly influence the cells lining the intestinal tract, such as enterocytes or goblet cells, which are responsible for intestinal enzyme synthesis and secretion [23,24,93]. It can be assumed that probiotics can promote the expression and release of digestive enzymes by these specialized cells, leading to higher enzyme levels in the gut, consequently affecting the utilization of nutrients, including phosphorus [20].

2.5. The Modulatory Effect of Temperature and Metabolism on Intestinal Absorption of Phosphorus in Farmed Fish

Apart from the nutritional parameters, phosphorus absorption in farmed fish is influenced by several factors, including water temperature and fish size [101]. Temperature in open flow fish farms can vary seasonally, but other factors, such as fish size, feeding regimes, and water flow, may also change, contributing to a range of interactions affecting phosphorus release from freshwater open flow fish farms. Bermudes et al. [102] found that increasing water temperature resulted in a significant increase in phosphorus absorption in juvenile barramundi (*Lates calcarifer*). The growth rate is significantly affected by thermal conditions and by growth parameters [103]. The changes in phosphorus requirements resulting from temperature, fish size, and life stage highlight the importance of considering the growth trajectory and physiological status of fish when formulating diets and managing phosphorus levels in their aquaculture systems. For example, body size affects the physiological processes and energy metabolism, and triploid fish may exhibit higher phosphorus requirements [104]; larvae and juvenile fish exhibit significant phosphorus requirements due to their rapid growth and increased tissue turnover [39]; larger fish have greater skeletal mass and overall body size, which necessitates the dietary absorption of phosphorus [6], whereas at older stages, gonadal development can also result in increased phosphorus requirements [105]. The above parameters can also interact with temperature, with low temperatures resulting in poor nutrient absorption and lower retention of dietary phosphorus, and high temperatures causing increased metabolic rates and nutrient requirements, potentially leading to increased feed intake and pollution [106].

Water temperature also affects the expression of genes related to nutrient absorption in the rainbow trout intestine [107]. The relationship between temperature and gene expression in fish intestines is complex and also influenced by diet, fish size, and water quality. High-protein diets and higher water temperatures influence specific gene expression related to amino acid and glucose transport [108,109].

3. Current and Potential Strategies for Reducing Phosphorus Pollution of FW Fish Farms

3.1. Phosphorus Waste Reduction Initiatives

Technological developments are playing a significant role in reducing the ecological impact of aquaculture systems, including addressing phosphorus pollution. Several advancements have emerged to improve water treatment efficiency and minimize the environmental impact of aquaculture effluents [110]. Open flow aquaculture systems may face greater challenges in managing and controlling phosphorus pollution compared to closed recirculating aquaculture systems (RAS); nevertheless, there are some similar principles of mechanical and biological filtration which can be applied to treat aquaculture effluents and minimize downstream phosphorus pollution. These include sedimentation and settling ponds, which can reduce the organic load and particulates in the effluents before they are discharged downstream in the aquatic ecosystem. The construction of wetlands or the cultivation of algae downstream of open flow fish farms can offer natural filtration mechanisms to utilize vegetation and soil to filter and absorb nutrients, including phosphorus, from the effluents. By promoting the growth of specific algae or plants, phosphorus can be effectively removed from the aquaculture effluents [111].

Nutrient management and feed optimization is also a highly effective method for reducing phosphorus pollution in fish farms [112], and the industry has made significant strides in this regard; the level of phosphorus in fish feeds has been significantly reduced, and feeding regimes have been optimized to reduce the phosphorus content of aquaculture wastes [9,113,114]. For example, supplementary feeding with cereals, such as wheat and other grains, is commonly practiced in semi-intensive aquaculture ponds for species like common carp. Cereals provide a low cost and readily available source of energy in fish feeds, but they contain antinutritional substances, including enzyme inhibitors, phytoestrogens, and oligosaccharides, which can reduce feed intake and nutrient bioavailability. These factors hinder phosphorus digestion and utilization, leading to slower growth and increased excreta in the water. Heat treatment, grinding, and the removal of hulls can mitigate the impact of antinutritional factors and improve feed digestibility. Furthermore, the use of pelleted or extruded feeds enhances digestibility, minimizes water pollution, and promotes better fish growth. Applying thermal and mechanical treatments to supplementary feeds prior to their use in aquaculture ponds can help reduce undigested or poorly digested feed, further improving efficiency and decreasing environmental impacts [115,116].

As a result, significant progress has been made in the past through the implementation of phosphorus waste reduction initiatives that have been developed and refined over the years [117,118]. These initiatives have relied on the application of best management practices, the optimization of feeding regimes, and the utilization of low-phosphorus feed ingredients. Moreover, promising results have been reported by incorporating feed supplements such as a-ketoglutarate [119] phytase enzymes [21,119,120], organic acids [74,121], and low-phosphorus plant protein combinations [122]. These strategies offer promising avenues to not only reduce phosphorus waste, but also to optimize fish growth and foster sustainable freshwater aquaculture practices. Likewise, exogenous enzymes can serve as a safe and efficient bio-additive to regulate various aspects of fish performance and reduce phosphorus pollution into the environment [79]. It can be concluded that incorporating exogenous enzymes into fish feed has the potential to improve growth performance, digestibility, feed utilization, whole-body composition, and immune performance, subsequently reducing phosphorus pollution in open flow freshwater fish farms.

3.2. Management Strategies for Reducing Phosphorous Pollution from Aquacultures

In fact, the aquaculture–environment interaction is an interesting paradox. On one hand, aquaculture effluents containing excess nutrients discharged into surrounding waters contribute to phosphorus release, with detrimental effects on the ecological state of the ecosystem. Aquaculture, on the other hand, is susceptible to the effects of eutrophication, as excessive phosphorus levels can disrupt the ecological balance, as well as the water quality, fish health, and growth. Recognizing this paradox, legislative initiatives are being implemented to address phosphorus pollution from various sources, including aquaculture and agriculture, to mitigate environmental impacts and promote sustainable aquaculture practices [123].

As a result, there are a variety of emerging or refined management strategies that can be used to reduce phosphorus pollution from aquaculture, including developing existing and new approaches, such as substituting fish meal with plant proteins and reducing the amount of phosphorus in the feed [69], optimizing feeding regimes to reduce FCR or daily feed intake, using water treatment technologies to remove phosphorus from wastewater, and developing sustainable aquaculture practices that reduce the environmental impact of fish farming [124–127]. However, the feasibility and effectiveness of these strategies depend on various factors, such as the type of aquaculture system, the type of fish being farmed, and the local environmental conditions. Phosphorus removal in open flow aquaculture systems within rivers is a critical concern for maintaining water quality and mitigating environmental impacts (Figure 3).

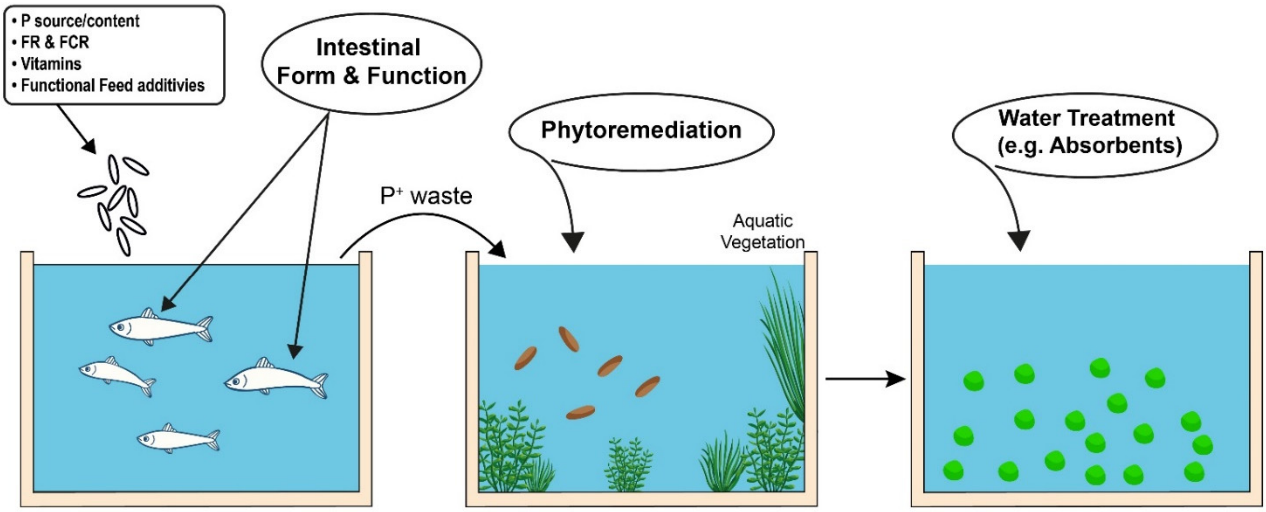

Figure 3. Interactions and strategies for phosphorus management in freshwater fish farms.

3.2.1. Phytoremediation

Emerging solutions such as phytoremediation and adsorbents/filtration offer promising approaches to address phosphorus pollution. These methods are based on the use of aquatic plants and mechanical and biological filters to remove excess phosphorus from the water [128–133]. Phytoremediation in river aquaculture can also be based on the use of floating aquatic plants, such as water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna* spp.), which have demonstrated effective nutrient removal capabilities [111,132]. These plants can be strategically placed in the aquaculture system or in constructed wetlands along the flow path of the river to help mitigate phosphorus pollution. Another example involves the utilization of effluent collected after wastewater treatment with *Rhodopseudomonas sphaeroides*. This effluent can be reutilized for microbial feed, medicament, and aquaculture water, specifically for the culture of common carp [46]. The integrated system of wastewater treatment and the use of effluent containing *R. sphaeroides* offer several benefits for the culture of common carp. Studies have shown that common carp raised in effluent containing *R. sphaeroides* exhibit improved survival rates, increased yield, and enhanced whole-body composition compared to those of the control groups. This effect is attributed to the presence of B vitamins in the effluent with *R. sphaeroides*, which enhance the activity of various enzymes and genes related to digestion, immunity, and antioxidant defense mechanisms [46]. Furthermore, the presence of *R. sphaeroides* in the effluent contributes to the improvement in aquaculture water quality, leading to reduced water pollution and wastewater discharge.

3.2.2. Adsorbents and Filtration Systems

Adsorbents and filtration systems are effective approaches for mitigating phosphorus and reducing eutrophication impacts in river-based aquaculture. Modified clays or activated carbon, acting as adsorbents, can bind to phosphorus particles in water, facilitating their removal. Similarly, filtration systems equipped with specific media or membranes can capture phosphorus particles. Zeolites, for instance, have demonstrated potential for removing phosphorus from aquaculture effluents [129]. Additionally, biomaterials derived from lodgepole pine have been utilized to reduce aquaculture waste and mitigate micronutrient-induced eutrophication. Treating rainbow trout effluents with these biomaterials for up to 60 min resulted in the removal of 150 to 180 g of phosphorus per metric ton, providing a method for eutrophication reduction in aquaculture [130]. The economic costs associated with these strategies can be a determinant of their potential applications in aquaculture. It is important to conduct thorough economic feasibility studies and cost-benefit analyses specific to each aquaculture operation to determine the financial viability and the return on investment of these solutions [132]. Factors such as potential cost savings from reduced water pollution, improved fish health, and regulatory compliance should also be considered.

3.3. The Role of Probiotics

Efforts to reduce the organic load of fish farms can utilize probiotics, which can affect phosphorus dynamics released by fish farms through their interaction with the intestinal microbiota of farmed fish. By incorporating probiotics into the fish diet or introducing them into the water column, it is possible to modulate the composition and activity of the gut microbiota, thereby enhancing the digestive capacity of fish in relation to phosphorus assimilation and utilization. Probiotics, when added to the fish diet or introduced into the water column, can alter gut microbiota and enhance the digestive capacity of fish. As a result of the improved functionality of the intestinal epithelium and the enhanced nutrient transport mechanisms facilitated by probiotics, nutrients, including phosphorus, are assimilated more efficiently. This enhanced assimilation leads to a reduction in phosphorus wastes, which is a critical issue in freshwater fish farms due to its environmental impact [8,17,36]. By increasing the efficiency of nutrient utilization, the amount of phosphorus excreted into the environment can be minimized. Following probiotic administration, the gut microbiota can contribute to enhance the nutrient utilization of the feed components and synthesize vitamins and amino acids, which can improve the nutritional value of the feed and enhance the digestion and absorption efficiency of nutrients. Several studies have shown that probiotics and prebiotics, which can promote the growth of beneficial gut bacteria, can improve the FCE and growth performance of fish. Certain strains of probiotic bacteria, when administered to aquaculture systems, have shown promise in improving phosphorus utilization and assimilation and reducing its release into the surrounding water [16,17].

Additionally, probiotics can also promote the growth of beneficial bacteria in the gut of fish, leading to enhanced nutrient absorption and utilization. This can result in improved feed conversion and reduced waste production, including phosphorus excretion. However, the effectiveness of probiotics in reducing phosphorus pollution can vary depending on several factors, including the specific probiotic strains used, the aquaculture system's characteristics, and the feed composition.

Apart from the traditional method of administering probiotics through diet, they can also be introduced into the aquatic environment, either by adding them to the water column or incorporating them into filtration systems [16,17]. This alternative approach allows probiotics to exert their effects on gut function and directly interact with the aquaculture water and sediment, potentially enhancing their remediation effects. For example, a study by Yi et al. [131] investigated the use of commercial probiotics immobilized in different carriers for aquaculture water and sediment remediation. Probiotics immobilized within oyster shells, vesuvianite, and walnut shells reduced the nutrient content in aquaculture water and sediment. Likewise, through competitive exclusion, the application of a mixture of probiotics, such as lactic acid bacteria, phototrophic bacteria, and yeast, can inhibit the growth of pathogenic and harmful bacteria in fish farms, as well as reduce phosphorus wastes. Jówiakowski et al. [109] reported a significant decrease (77.6%) in phosphorus concentrations in the water from an aquaculture pond following the application of a mixture of probiotics. These findings suggest that probiotics can not only function as dietary components, but they can also contribute to bioremediation efforts, ultimately improving water quality parameters and reducing nutrient loads in aquaculture effluents. However, further research is still needed to optimize the use of probiotics for phosphorus management in freshwater aquaculture, as their effectiveness can vary depending on factors such as bacterial strains, aquaculture system characteristics, and feed composition. Table 1 presents an overview of some issues and parameters which are implicated in phosphorus pollution and remediation strategies.

Table 1. Phosphorus pollution in open water freshwater fish farms: issues and possible remediation.

Issue	Main Contributing Parameter	Possible Remediation
Phosphorus pollution in open flow fish farming	Phosphorus in fish feeds and feed conversion rate	New fish feed formulations, improved efficiency of intestinal phosphorus absorption [10,68,75–79,83,84,112–114,117]
Gut health and nutrient absorption	Feeding regime, substitution of fish meal, intestinal inflammation	Pre and probiotics, functional feed additives, and fish health management [94–97,100,104,119,122]
Efficient aquaculture effluent treatments	Water flow rate, fish density	Phytoremediation and filtering [46,88,109,111,124,126–135].

4. Conclusions and Perspectives

The data reviewed in the previous sections indicate that phosphorus retention efficiency of different farmed fish species can vary due to factors such as their physiological characteristics, feeding habits, and digestive physiology. The phosphorus requirements and absorption mechanisms can differ among fish species, with some species exhibiting specialized adaptations in their intestines.

While several methods and strategies can contribute to reducing phosphorus pollution from fish farms, a holistic approach encompassing various factors should be considered. Cost analysis [134], proper feed management [45], water quality monitoring, and nutrient cycling play pivotal roles in effectively addressing phosphorus-related environmental concerns [17]. By understanding the mechanisms of phosphorus absorption, dietary factors, anti-nutritional substances, and intestinal morphology, we can optimize aquaculture practices to reduce phosphorus release.

Author Contributions: Conceptualization, C.N. and M.K.; methodology, C.N., M.K. and M.T.; software, T.M.; validation, M.K. and E.G.; formal analysis, M.K.; investigation, C.N., M.K. and T.M.; resources, C.N. and H.K.; writing—original draft preparation, C.N., H.K. and M.K.; writing—review and editing, C.N., E.G. and H.K.; visualization, C.N., M.K. and E.G.; supervision, C.N.; project administration, C.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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