Received: 6 January 2024 | Revised: 11 April 2024 | Accepted: 17 April 2024

DOI: 10.1111/raq.12921

REVIEW

REVIEWS IN Aquaculture

A review of the benefits and limitations of waste nutrient treatment in aquaculture pond facilities

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Funding information
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Abstract

Managing waste nutrients from intensive freshwater and marine pond aquaculture is a global challenge. Nutrient-enriched water released from farms can have detrimental effects on aquatic ecosystem health. There are a range of treatment options for discharge water from fish and crustacean ponds, and this review examines the benefits and limitations of these options. Much of the nutrient waste is derived from the addition of formulated feed. In recent years, reduction in waste from feeds and feeding has been largely incremental. In terms of treatment, there are low-cost approaches, such as settlement ponds, but they are inefficient at reducing nutrients. Biological systems, using aquatic plants, microalgae and filter feeders to reduce nutrient release from farms have variable levels of effectiveness. Establishing wetlands requires considerable additional land area, and success to date has been highly variable. Overall, this review found no simple cost-effective solution for managing nutrient enriched water from ponds. This is due, in many cases, to challenges with treating the large volumes of discharge water with relatively low nutrient concentrations. This means that more technologically advanced and reliable treatment options, for example, bioreactors, are prohibitively expensive. However, some systems, such as use of recirculation systems typically increase nutrient concentrations, and hence the efficiency and effectiveness of more expensive treatment methods. Biofloc systems can also provide a mechanism for in-situ nutrient treatment as well as a supplementary food source for animals. Overall, there is scope to improve treatment of waste nutrients, but significant modifications to many production systems are needed to achieve this.

KEYWORDS
fish aquaculture, nitrogen, phosphorus, shrimp aquaculture, treatment systems

1 | INTRODUCTION

Worldwide, during the 30 years from 1990 to 2020, aquaculture production grew at 6.7% annually to reach a total of 122.6 million tonnes in 2020.[1] This included 87.5 million tonnes of aquatic animal production (fish, molluscs and crustaceans). Although the production methods and facilities vary widely, land-based production of finfish and crustaceans typically use earthen ponds. Data for the total global area of aquaculture ponds are not readily available, but a recent paper used satellite remote sensing data to estimate the coastal pond aquaculture area in Asia.[2] They estimated more than 3.4 million aquaculture ponds existed within 200 km of the coastlines of South Asia,

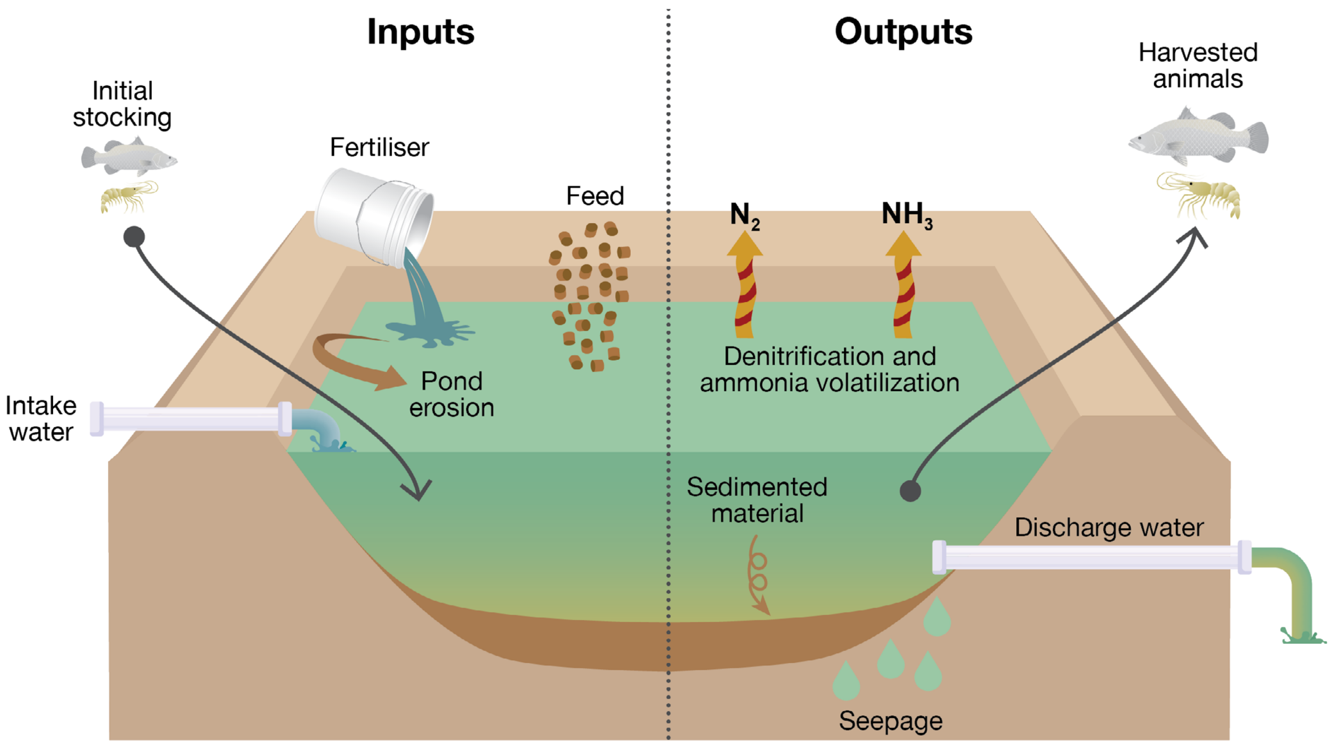

FIGURE 1 Nutrient inputs and outputs in a typical aquaculture production pond.

Southeast Asia and East Asia. These had a combined area of more than 2 million hectares, with 45% of the mapped ponds being located within 5 km of the coast.

The Food and Agriculture Organization (FAO) expects aquatic food production to increase by 15% by 2030, mostly through the expansion and intensification of aquaculture.[1] Aquaculture production can be defined from extensive to intensive based on the level of inputs and outputs. In 1993, the farming systems for shrimp production were defined based on the stocking density, feed sources and production output.[3] Extensive production was defined as using a low stocking density (e.g., 1–3 shrimp m^{-2}), relying on natural food items with occasional supplemental feeding, and production up to 800 kg ha^{-1}. Intensive production was defined as being stocked at ~10–30 shrimp m^{-2}, relying on manufactured feeds, and producing 3–6 t ha^{-1}. Semi-intensive production sat between extensive and intensive production, relying on both natural feed and supplemental feeding. Since these definitions were proposed, more efficient feed, feeding and management systems have increased the production per hectare for the same stocking density. In recent years, there has been a move to further intensify production using raceways and highly controlled production systems to achieve stocking densities of 150 or more shrimp m^{-2} (termed 'super-intensive').[4] Therefore, in 2020 a more up-to-date definition of intensity of production in terms of input, treatment and output functions for all aquaculture production systems was developed.[5]

Intensification also results in an increase in nutrient loads in ponds, also known as 'system loading'.[6] While there is some processing of nutrients within the ponds and farms more broadly, discharge of nutrients into the adjacent aquatic environment, known as 'environmental loading', can have negative impacts.[7,8] This includes water quality impacts, such as increased algal growth and reduced oxygen levels, which may impact on the flora and fauna in rivers, estuaries and the coastal zone.[9] The level of impact is dependent upon several factors including the species being grown, stocking density, production system and management practices, along with feed quality.[10] This review examines nutrient inputs and outputs from intensive aquaculture ponds and identifies approaches/technologies that are being used to ameliorate nutrients, and hence reduce downstream impacts.

2 | AQUACULTURE POND NUTRIENT BUDGETS

Designing a treatment system to reduce the release of nutrients from a pond aquaculture facility requires an understanding of the nutrient load and water volume which needs to be treated throughout the production cycle. Nutrient budgets are a simple mass balance exercise in which all nutrient inputs and outputs are totaled, allowing an assessment of the relative importance of each nutrient input and output within the production system (Figure 1).

Nutrient budgets typically provide an estimate of inputs and outputs over a production period. Budgets for nitrogen and phosphorus have been calculated for fish and crustaceans, in both fresh and saltwater pond environments on a whole-of-production season basis. The relative contributions of different inputs of nutrients (as well as solids and organic matter) are affected by pond construction, soil type and erodibility, feed inputs, animal stocking densities, and the intensity of aeration and circulation within the pond. Sedimented material remaining from previous crops will also impact the relative contributions of soils as a source of nutrients in the budget. Microalgae, detritus, and microbes within the pond will contribute to both the settled solids and suspended solids fractions of the budget. However, estimating the proportion of these different inputs has a relatively high level of uncertainty, due to multiple factors, such as the state of the algal bloom and hence nutrient content in this fraction, the amount of flushing of pond water that is occurring and the level of soil erosion.

Pond systems are more dynamic within a growth season than can be reflected in these budgets. As an example, temperature can affect feed intake, digestibility and feed utilization and the amount of waste produced by barramundi.[11] A decline in temperature from 32 to 23°C caused greater use of nitrogen as a metabolite, resulting in an increase in nitrogen excretion. Phosphorus was also poorly retained at lower temperatures, due to reduced digestibility and slower growth reducing demand for the mineral.

2.1 | Nutrient inputs

In pond-based aquaculture systems, the nutrient inputs over the growth season (Figure 1) may include:

- Water used to fill the system
- Water exchange required through the production cycle to maintain water quality and animal health
- Fertilizers used to promote algal blooms and secondary production within the pond
- Animals initially stocked into the ponds
- Rainfall and runoff entering the pond during the production cycle
- Erosion of earthen ponds
- Formulated feeds
- Nitrogen fixation by cyanobacteria

Fertilizers are typically used early in the production cycle, to promote algal blooms which in turn feed the zooplankton and benthic biota in the pond. This natural productivity needs to be supplemented with formulated feed in intensive and super-intensive systems, and as the animal biomass increases through the production cycle. Quantification of budgets for semi-intensive and intensive production systems showed that formulated feeds typically contribute between 80% and 97% of the nitrogen input to a pond.[12–19] In freshwater ponds with lined walls, one study in striped bass (*Morone saxatilis*) ponds reported that feed contributed about 75% of the phosphorus inputs to the pond with the remainder coming from intake water, rainfall and runoff.[13] Another study of channel catfish (*Ictalurus punctatus*) ponds found that feed contributed 97% of the phosphorus input.[20] In earthen brackish water shrimp (*Penaeus monodon*) ponds, where the erosion of soil, and sediments from previous crops may be a larger load, feed contributed only 51%, while erosion of the soil provided 26% of the total phosphorus input.[15] Fertilizers typically only contribute around 2% to 5% of the nitrogen input[15,18,19] and around 3% to 21% of the total phosphorus input.[15,18] The nitrogen load in intake water depends on the quality of the adjacent water pumped into the ponds. In areas with a high density of farms, intake water can have a relatively high nitrogen load as it may contain discharge water from other farms.

Nitrogen fixation by certain species of cyanobacteria may contribute nitrogen to a pond system,[21] particularly in freshwater systems. However, nitrogen fixation does not occur when dissolved inorganic nitrogen (DIN) concentrations are relatively high, as is typical in intensive aquaculture ponds so it is considered a minor input and not reported in most studies.[12,21]

2.2 | Nutrient outputs

In addition to the inputs, there are also several nutrient outputs from production ponds over a growth season (Table 1).

2.2.1 | Harvested animal biomass

The nutrients, in the form of formulated feed and pond biota input to ponds are used for growth and development, and maintenance of metabolic functions. However, not all ingested nutrients are retained by animals and will be lost through faeces and metabolic processes within the animal. Nitrogen is excreted by fish and crustaceans through the gills as ammonia ($NH_3 + NH_4^+$), and will leach from faeces as both organic (including urea) and inorganic nitrogen.[22] Additionally, the feed itself can leach considerable amounts of organic nitrogen. Urea and phosphate may also be excreted by the kidneys of fish,[23] while in crustaceans, the exuviae from the moulting cycle also contributes to nutrient and mineral loss.[24] As a result, harvested crustaceans account for only a moderate proportion of the nitrogen input, usually around 20% to 37%.[15,17–19,25–27] Similarly, harvested fish account for 16% to 36% of nitrogen input.[12,14,28–31]

The phosphorus content of shrimp does not appear to change markedly from stocking to harvest.[25] Reported levels of phosphorus for *P. monodon* range from 26 to 34 mg P kg^{-1} liveweight,[32,33] and similarly for *P. vannamei*, 36 mg P kg^{-1} liveweight.[25] Phosphorus retention has been reported to range from 6% to 11%[18,34] for *P. monodon*, and 11% for *P. vannamei*.[25]

The phosphorus content of fish will change through the lifecycle, but the largest variation is between species. Channel catfish have a relatively low level of phosphorus in their body (1.9 to 2.9 g P kg^{-1} liveweight) so the proportion of the phosphorus inputs that are retained by the harvested fish is only 15% to 30%.[12,20] Striped bass contain more phosphorus and so retained 42% of the phosphorus input when fed feeds with similar levels of total phosphorus.[13] Another species, barramundi (*Lates calcarifer*), also have a higher level of phosphorus in their body, that is, 9 to 11 g P kg^{-1} liveweight, with a reported retention efficiency of phosphorus supplied by the feed between 35% and 55%.[35,36]

TABLE 1 Studies of nutrient outputs (as a % of inputs) for fish and shrimp aquaculture ponds.

	Species	Salinity	Daily exchange rate[a]	Proportion of input (%)											Reference
				Animal biomass		Sedimented material		Seepage		Discharge water		$N_2 + NH_3$ processes	Unaccounted		
				N	P	N	P	N	P	N	P	N	N	P	
Fish	*Ictalurus punctatus*	Freshwater	0%	25	30		55	11	8	7	7	57			Boyd (1985)[12]
Fish	*Morone saxatilis*	Brackish	0%	20	42		53			25	47	55			Daniels and Boyd (1989)[13]
Fish	*Sparus aurata*	Seawater	48%	26	21	10	17			59	72		5	−10	Krom and Neori (1989)[29]
Fish	*Oreochromis* sp.	Freshwater	0%	22		67				1		1	9		Acosta-Nassar et al. (1994)[14]
Fish	*Ictalurus punctatus*	Freshwater	0%		19		76				5				Gross et al. (1998)[20]
Shrimp	*P. monodon*	Seawater	2%–5%	21	6	31	84	0.1	0.02	35	10	13			Briggs and Funge-Smith (1994)[15]
Shrimp	*P. monodon*	Seawater	2%–5%	18	6	24	84	0.1	0.02	27	10	31			Funge-Smith and Briggs (1998)[34]
Shrimp	*P. monodon* & *P. merguiensis*	Seawater	4%	26		14				57		3			Jackson et al. (2003a)[17]
Shrimp	*P. monodon*	Brackish	0%	30	11	50	65			7	3		13	22	Sahu et al. (2012)[18]
Shrimp	*M. rosenbergii*	Freshwater	0%	37	10	52	76			3	2		9	13	Adhikari et al. (2014)[19]
Shrimp	*P. vannamei*	Brackish	NR	35	24	38	57			18	6		10	13	Luu et al. (2018)[27]
Shrimp	*P. monodon*	Brackish	NR	27	13	40	57			24	9		9	21	
Shrimp	*P. vannamei*	Brackish	44%	24		18				51		7			Chen et al. (2018)[38]
Range of values				18–37	6–42	10–67	17–84	0.1–11	0.02–8	1–59	2–72	1–57	5–13	−10–+22	

Abbreviations: $N_2 + NH_3$ processes, estimated loss of nitrogen through denitrification and ammonia volatilization; NR, not reported.
[a]Average daily exchange rate as reported.

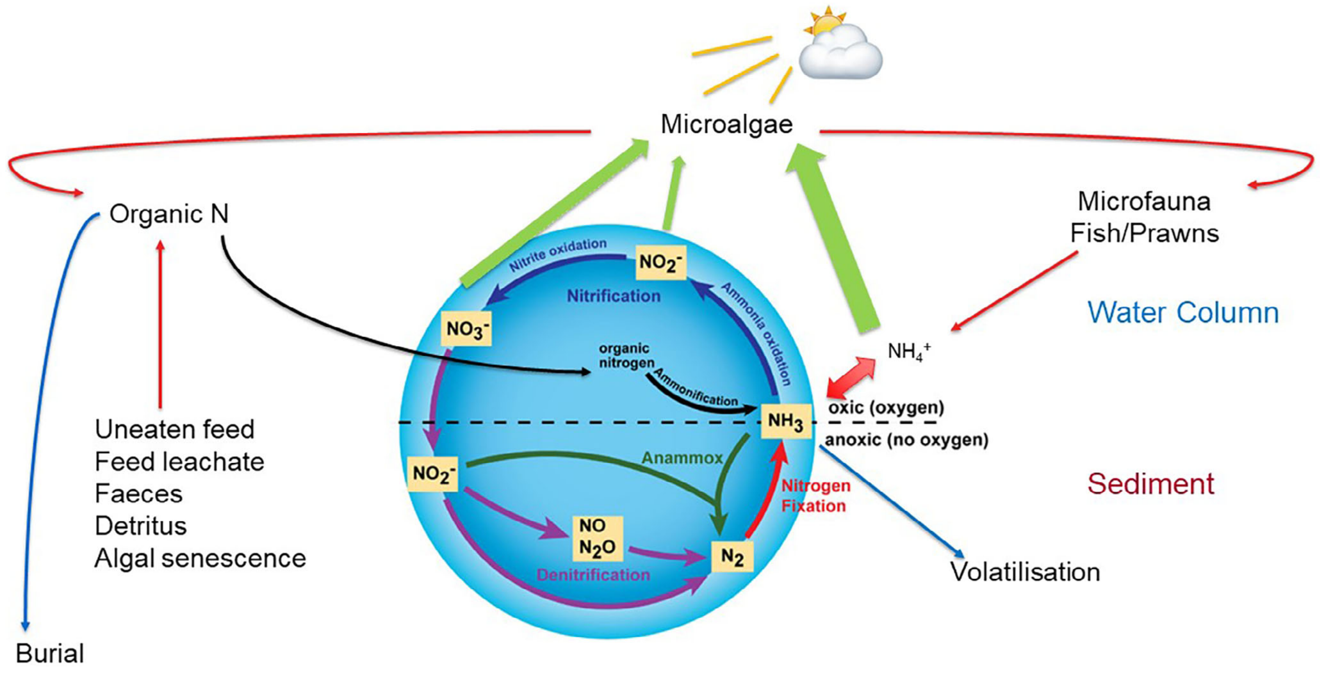

FIGURE 2 Nitrogen transformation processes within a pond environment. Adapted from: Bernhard (2010).[210]

2.2.2 | Sedimentation

Particulate matter in ponds, subject to the mixing and aeration regimes, will gradually accumulate on the bottom of the pond over the growth season. This will include inorganic particulate matter, that is, eroded soil in unlined ponds, suspended material imported in the intake water, and organic matter from uneaten feed, faeces, senescent microalgae and other detritus.[37] Sedimentation is an important process in the pond system, constantly removing nutrients and other waste from the water column, although the resuspension of this material is possible due to the shallowness of aquaculture ponds, bioturbation and water movement. Sedimentation of nitrogen in particulate matter in shrimp ponds varies considerably ranging from 14% to 52% of the input over a growth season.[15–17,34,36] There is similar variability in the nitrogen deposition loads in fish pond sediments, with no accumulation in a study of channel catfish and striped bass ponds,[12,13] while another study reported 23%. A study of tilapia (*Oreochromis* sp.) ponds measured 67% to 70%.[14,39]

While nitrogen may accumulate in pond sediments, the low oxygen conditions in this environment may result in a proportion of this nitrogen being remineralized by microbes and released as ammonia.[40] Modelling of pond data has demonstrated the benefits of removing sedimented material to reduce ammonia release, thereby reducing nitrogen discharge from production ponds.[41] One mechanism for reducing nitrogen remineralization is the use of central drains which drain out the accumulated sludge. However, the sludge still needs to be processed and/or stored so that it does not ultimately end up back in the natural aquatic environment.

The earthen pond bottom is the main sink for phosphorus in pond systems, as suspended soil particles chemically bind dissolved inorganic phosphorus. The common management practice of liming ponds encourages the formation of calcium phosphate, increasing the sequestration ability of the soils.[42] Sedimentation of phosphorus may be further enhanced by the precipitation of dissolved calcium phosphate at pH 8–8.5. A study of channel catfish ponds found that sediments accounted for 76% of the phosphorus input in channel catfish ponds,[20] with the same proportion for freshwater prawn (*Macrobrachium rosenbergii*) ponds.[18] Only 53% was sedimented in striped bass ponds.[13] In shrimp ponds, sedimentation accounted for around 84% of the phosphorus.[15,25]

2.2.3 | Other nutrient transformation processes

Nutrients can also be cycled via biological processes within ponds (Figure 2). Nitrification is a relatively slow process converting ammonia, which is excreted by animals and released from sedimented material, to nitrate. However, it will only be an important process when water residence times are longer.[43] Nitrate is the precursor needed for denitrification, which converts nitrate to nitrogen gas (N_2) through anaerobic microbial processes, resulting in nitrogen loss from ponds. Nitrate availability may limit denitrification, while organic carbon availability is likely to be high as a result of algal bloom cycles. Additionally, anaerobic ammonia oxidation or anammox is another microbial process which can contribute to nitrogen loss through the production of N_2.[44] Nitrogen may also be lost to the atmosphere through ammonia volatilization, although this process does not appear to result in a major loss of nitrogen from aquaculture ponds.[30]

Denitrification, anammox and ammonia volatilization rates are well recognized processes resulting in nitrogen outputs from aquaculture ponds, but they are rarely measured in nutrient budget studies due to the expense and complexity of analyses. Where these processes are measured, it is often estimated indirectly as the difference between inputs and the measured outputs from the pond, or stoichiometrically. The percentage removed ranges from 3% to 47% depending on the study.[10,13,15,29,36,45]

In a study where denitrification was measured in shrimp ponds, the percentage removed was less than 2%.[40] Similarly, in a tropical freshwater fish pond, denitrification rates removed just 1% of the nitrogen input.[14] Another study found that the anammox process contributed very little, if any, to N_2 production from sediment in aquaculture settlement ponds, and overall denitrification and anammox only removed about 2.5% of the nitrogen input.[46]

2.2.4 | Pond discharge loads

Nutrients which are not incorporated into any of the outputs/sinks outlined above will eventually be discharged from the pond through routine water exchanges or final draining at harvest. Therefore, the proportion of input nutrient that is discharged will depend on the effectiveness of other outputs, that is, harvested animals, sedimentation, gaseous exchange, in removing nutrients from the water column. Routine water exchange is typically used to manage algal blooms, maintain other aspects of water quality, and protect the health of animals. Nitrogen budgets developed for shrimp ponds have found that discharge can account for between 3% and 57% of the nitrogen input.[15,17–19,27,34,38] While discharge also accounted for between 2% and 45% of the phosphorus input.[15,42,47]

Water discharge from fish ponds accounted for a similar range (1% to 59%) of the nitrogen inputs to that for shrimp ponds. Phosphorus budgets are even more variable (5% to 72%), partly due to the wide range of water exchange rates that were used in these studies.[12–14,20,29] Improved management techniques and algal bloom control have resulted in a reduction in water exchange rates used by the pond aquaculture industry over time, reducing total nutrient discharge.[48]

2.3 | Nutrient characteristics of aquaculture pond discharge

Nutrients, that is, nitrogen and phosphorus, are released from aquaculture ponds in a range of forms. In terms of nitrogen, DIN, mostly ammonia, is derived from excretion by the production animals and remineralized organic matter released from sediments on the pond bottom.[22,40] It is highly dynamic with concentrations of ammonia varying rapidly and substantially. Microalgae are one of the dominant components of particulate nitrogen in aquaculture ponds.[49–51] Microalgae are very effective at ammonia uptake, but when the assimilative capacity of the microalgal population is exceeded, ammonia concentrations rise.

The scale of algal blooms varies substantially from day to day, and water exchange is often used to manage nutrient concentrations and algal bloom density. A study in a marine fish pond during a period with low biomass of microalgae in the water, that is, low chlorophyll *a* levels (after a 'microalgal crash'), showed that total nitrogen (TN) discharge was half that from the same pond when the algae were blooming.[29] At the same time the dissolved nitrogen concentrations increased almost four-fold in the discharge compared with when microalgal biomass was relatively high. Phosphorus discharge displayed a similar pattern between bloom and non-bloom periods, albeit with a smaller magnitude of change. The same study also showed an increase in ammonia at night when microalgal uptake is reduced. These daily and diel variations in dissolved nutrients typically occur in outdoor ponds and have also been demonstrated in shrimp ponds.[52,53]

The other form of nitrogen in ponds is dissolved organic nitrogen (DON), derived primarily from feeds and feeding. The bulk of it is refractory, so cannot be utilized by microalgae, except for urea and dissolved free amino acids, and is slowly broken down by microbes. Therefore, it has less impact on ecosystem health in the adjacent waters in the short term.[22,54] DON typically accumulates over the growth season.

Most of the phosphorus discharged from aquaculture ponds is typically in particulate form, with low concentrations of dissolved organic and inorganic phosphorus. These low concentrations are due to microalgal uptake, particularly inorganic phosphorus, that is, phosphate. The concentration of TN, and the proportion of ammonia discharged from a shrimp farm has also been shown to vary substantially from day-to-day.[17] The rate of water exchange typically increases over the production season as the nutrient loading on the pond increases, but it is also governed by the health and scale of the microalgal bloom.

3 | TECHNOLOGIES AND APPROACHES FOR REDUCING NUTRIENT INPUTS TO PONDS

Obviously, one way to limit the nutrient load discharged from a pond over the production cycle is to simply reduce the amount of nutrient added to the pond during that cycle. Water used to fill the ponds and for exchange throughout the crop can make a significant contribution to the overall nutrient input depending on the exchange rate and the nutrient concentrations in the source water. A nutrient budget study for shrimp showed that with an exchange rate of 2.5% d^{-1} the source water contributed 314 kg N ha^{-1} over the crop, which was about one third of the amount of N added through the feed.[48] However, when an exchange rate of 25% was used, the nitrogen input from the water increased to more than 3 t ha^{-1}. Generally, although variable, the nutrient contribution from source water is a smaller component of the total nutrient input. Improved management practices have reduced exchange rates used in pond production.[48]

3.1 | Feeds

Feed is a major contributor to the cost of production in semi-intensive and intensive aquaculture systems.[1,55] While farm costs and feed commodity prices have been increasing, the farm gate prices for aquaculture product have not kept pace with these increases, meaning that margins have diminished, driving a push for intensification and other production efficiencies.[56] Beyond the financial cost, feed is also the main input of nutrients in the pond system. Therefore, there are dual incentives for improvements in feed and feeding within the aquaculture industry, being financial savings and environmental benefits.

Aquatic animals have an energetic advantage over terrestrial animals in that nitrogenous waste is able to be directly excreted without conversion to urea or uric acid. Therefore, more energy from protein catabolism is available for metabolic functions and growth.[57–59] The excretory products of protein catabolism (ammonia and urea) result in 40% to 60% of the nitrogen ingested from food being excreted within 24 h in fish.[60] Undigested protein in faeces and uneaten food contribute to the organic nitrogen load in the pond. Carnivorous fish require a diet that is relatively high in protein and low in carbohydrates,[58,61] using excess dietary protein as an energy source.

Similarly, although more omnivorous, shrimp also utilize dietary protein for energy as they have a limited capacity to store lipids and carbohydrates.[62] The optimal feed protein level for *P. monodon* is 35% to 40% when grown in seawater with an algal bloom,[63] while the analyzed protein levels of several commercial feeds for *P. vannamei* ranged from 25% to 49%[6] Catabolism results in ammonia excretion from the gills with the rate increasing at about 2 h after feeding, returning to the basal rate around 5–6 h after feeding.[64] Shrimp also excrete nitrogen in faeces.[22]

Fish and crustaceans have a requirement for phosphorus which must be met through their diet.[65,66] The dietary phosphorus requirement for barramundi is around 0.65%,[67] while the reported requirement for *P. monodon* is 0.74%.[68]

A reduction in nutrient waste from feeds may be achieved through species-specific optimization of dietary requirements and using feed materials that offer improved digestibility and increased bioavailability.[66] The food conversion ratio (FCR) is a simple measure of the efficiency with which a feed is converted into animal biomass over the culture period. In a pond situation, it is the amount of feed input (as fed) relative to the amount of harvested biomass. Improving the FCR will reduce the nutrient input required to produce each tonne of fish or shrimp. The potential of aquaculture feeds to contribute to the waste load has been calculated for a range of commercial grower feeds.[6] The feeds examined in this study were produced for five species, including marine and freshwater fish and the shrimp species, *P. vannamei*. These authors showed that although the contribution of aquaculture to the estimates of global anthropogenic release was small, a minor change in FCR (0.1) could provide a substantial reduction in total feed used, and resulting nutrient waste, and associated feed costs across the five species.

Research into both the nutritional requirements of many cultured species, and the array of materials used for feed production has provided the basis for improved feeds and reduced FCRs over time.[66] There have been significant improvements in the utilization of phosphorus in fish through an understanding of metabolic requirements and the availability of phosphorus in the feed used to meet these levels.[66] However, there is a limit to the reduction in essential nutrients that can be achieved before growth is affected.

Commercial feed manufacturing methods have also improved. The use of extrusion technology for fish feeds can both eliminate the need to use indigestible binders and improve the digestibility of some materials used in the feed. Moreover, it allows control of the pellet structure to enable production of higher lipid feeds, and the ability to control feed density to produce floating or sinking pellets. Therefore, pellets can be tailored to the requirements and feeding habits of different species. While there are advantages for the more expensive extrusion technology in the manufacture of fish feed, shrimp feed has traditionally been steam-pelleted. The growth performance and pellet physical characteristics of extruded and steam-pelleted shrimp feeds have recently been compared in *P. vannamei*.[69] While extrusion produced a slightly more durable pellet, once the pellets were immersed in water, the stability of the pellets did not differ to steam-pelleted, even after 60 min soaking. More importantly, the growth performance and FCRs of the animals on each feed did not differ. Therefore, this suggests that extrusion is not required to produce a quality shrimp feed, however manufacturers may move to use this technology as the costs have reduced.

3.2 | Management of feeding

Management of feed inputs is an important factor in reducing nutrient discharge from pond systems, by maximizing the utilization of the feed and its' conversion into animal biomass. Effectively managing feeding in an aquatic environment is more challenging than terrestrial farming. Behavioural differences between species, and individuals within a species adds to the complexity. Some fish species will feed on floating pellets, while others prefer to feed below the surface. Hierarchical behaviour is common, where some animals will outcompete others for feed, making it difficult to monitor and control the effectiveness of feeding. Multiple daily feedings may overcome some of these issues,[55] but monitoring of the feeding responses is important in ensuring that all the animals can meet their growth potential. Camera systems are used to monitor feeding in some offshore fish cages,[70] allowing less dominant fish to consume pellets sinking through the water column. However, these systems are not currently suited to shallow, turbid pond environments. Therefore, although some fish species, for example, barramundi, can be reluctant to feed on the surface if the water is too clear,[71] floating feeds may be preferred as the surface feeding response can be monitored by the feeder, and overfeeding reduced.

Shrimp require a sinking pellet and rely on chemical cues to detect food, rather than visual stimuli. While many fish will swallow pellets whole, shrimp consume food more slowly, grinding particles from the pellet with their mouthparts and then scraping them into the

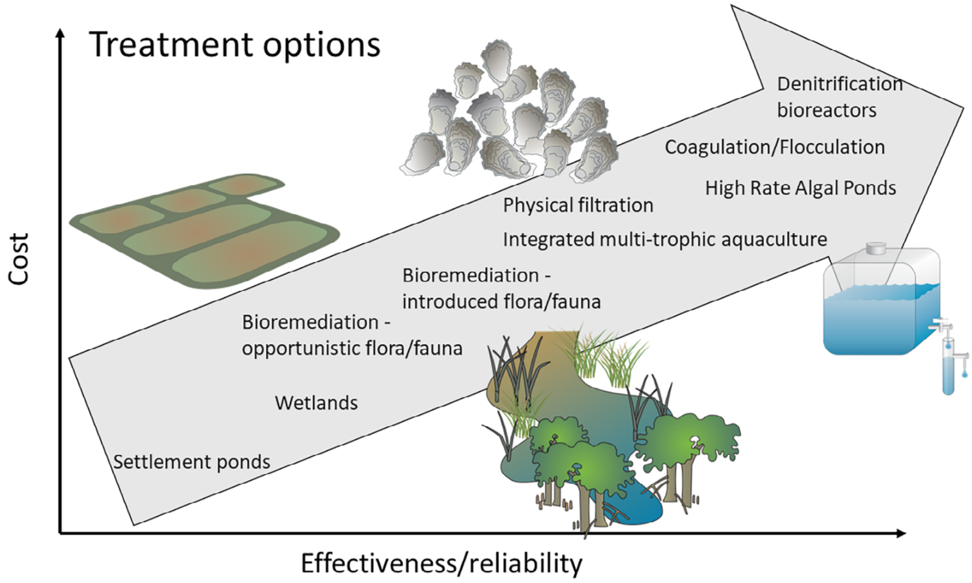

FIGURE 3 Treatment options scaled according to relative cost and effectiveness/reliability.

mouth.[72,73] This process leads to significant feed wastage through particle loss and nutrient leaching.[22] Monitoring feed intake in shrimp is more difficult and has relied upon manual methods like feed trays, along with the knowledge and experience of the feeder to adjust feeding rates for subsequent feeds. However, these approaches are responsive, rather than proactive, adjusting feeding based on the previous feed addition.

Automatic feeding systems and decision support tools are emerging approaches that can be useful in reducing FCRs, and thereby reducing nutrient waste in ponds.[74] However, some of these technologies are still developmental. Passive acoustic feeding systems are commercially available for fish, and similar technology has been developed for shrimp, based on the audible noise that shrimp make when eating.[72] This technology has improved growth rates and yield of *P. vannamei* in commercial production,[75,76] reducing FCRs and feed wastage.

4 | TREATMENT OPTIONS FOR NUTRIENT-RICH DISCHARGE WATER

Reducing the nutrient input to ponds and increasing the efficiency of nutrient retention within the harvested animals are important aspects of managing nutrient loads and reducing the potential impact of aquaculture on the surrounding aquatic environment. However, there will inevitably be a nutrient load that requires treatment prior to release into the natural environment. There are a range of approaches used to treat pond nutrients, with some methods well-established and other new approaches continually being evaluated. Based on the examination of the scientific literature, it appears that there is little consistency in the treatment methods used, limited reliable information on the effectiveness of these methods at a farm scale; and limited information on the cost-effectiveness of these methods. The existing information from scientific publications is outlined below (Figure 3).

4.1 | Settlement ponds

Settlement ponds have been widely used as a form of primary treatment for production pond discharge water. They are designed to increase water residence time, reduce the velocity of flow, and minimize turbulence to encourage the sedimentation of particulate material from the water column.[77] Studies have shown that settlement ponds can achieve a reduction in total suspended solids (TSS) as high as 88%.[78] However, these ponds are less efficient at removing nitrogen (10%–31% TN) and phosphorus (15%–55% TP).[32,78,79] One reason for this is that many microalgae do not settle, so may remain in the water column. Additionally, sedimented material contains nitrogen and phosphorus which may remineralize under hypoxic conditions, releasing nutrients back into the water column. One study, using production ponds rather than settlement ponds, measured a release rate of 6% day^{-1}.[140] However, it is likely that this rate would be similar in settlement ponds since the sediment inputs are the same. Settlement ponds may also be suitable for production of N_2 gas through denitrification and anammox of waste nitrogen. Studies in shrimp and barramundi settlement ponds found potential rates similar to those of a subtropical constructed wetland.[46] Conversely, the organic-rich sediment layers produce hydrogen sulphide which inhibits processes such as nitrification, with flow-on effects to denitrification.[80] So, while potential rates were high, the estimation of total N reduction in these settlement ponds was just 2.5%.[46] Therefore, optimization of design and day-to-day management of settlement ponds is needed to enhance denitrification.

Phosphorus is typically more effectively sedimented than nitrogen.[79] This is because much of the phosphorus is bound to soil and other particles. However, as with nitrogen, it may be remineralized under hypoxic conditions, with dissolved phosphorus being released into the water column.[40]

Sedimented material will, over time, also reduce the effective volume of the settlement pond, in turn reducing the time that the water is detained within the pond (hydraulic retention time [HRT]).[81] Periodic removal of this organic-rich sedimented material is required to maintain the efficiency of nutrient removal in a settlement pond. It has been suggested that an HRT of 2–3 days should reduce TN by 15%–25% and TP by up to 35%.[32] To achieve this HRT, they suggested that between 10% and 25% of the production pond area needs to be allocated to settlement ponds. However, studies have also showed that HRT was not the only factor affecting the efficiency of nutrient removal in shrimp ponds.[79] Overall, it is clear from the available research that TN reduction through settlement is only modest, typically considerably less than 50%.

4.2 | Bioremediation

There are several mechanisms through which biota can reduce nutrient release from aquaculture farms. Flora and fauna that are naturally occurring in the water, sediment and on structures within a treatment system may be used—which will be referred to as opportunistic bioremediation by pre-existing flora and fauna. The other approach is culturing animals or plants within a treatment system—bioremediation through introduced flora and fauna.

4.2.1 | Opportunistic bioremediation by pre-existing flora and fauna

The simplest method for treating discharge water from freshwater aquaculture facilities is irrigation and/or the use of sedimented material as fertilizer,[31,82] although accumulated salts from feed and feeding need to be monitored to ensure that the soil structure and terrestrial plant growth are not compromised. Additionally, it may be impractical to continuously utilize the large volumes of water without the availability of major storage infrastructure.

The efficacy of treatment ponds for nitrogen and phosphorus removal can be affected by the presence of animals and plants which opportunistically colonize these ponds. Filter feeders, for example, which colonize hard surfaces within both production and treatment ponds (e.g., barnacles, tubeworms and bivalves) can remove particulate nitrogen, including microalgae. Naturally occurring benthic algae, macroalgae (marine and brackish waters) or aquatic plants (freshwaters) will incorporate DIN and phosphorus into biomass. Naturally occurring species of filamentous algae have been evaluated for their potential to remove nitrogen from settlement ponds.[83] Under optimal conditions, modelling estimated that 4 t of *Cladophora* regularly harvested can remove a maximum of about 23 kg nitrogen from the system.

Microalgal phycoremediation is used for a variety of applications including agricultural, industrial and municipal wastewater treatment,[84,85] but has also been used in treatment systems for recirculating aquaculture systems (RAS).[86] While algae are efficient at removing dissolved nutrients, ultimately the microalgal cells also need to be removed from the water to reduce the total nutrient load being released to the aquatic environment. This requires further treatment, for example through the addition of chemical or biological flocculants, and settlement or filtration.[87,88] Filter feeders[32] can have a significant impact on microalgal biomass, depending on the surface area available for colonization.[32] However, a study examining the effect of barnacles in a settlement system for *P. vannamei* production showed only a modest (8%) reduction in TN, although this system had an HRT of just 6 h.[89]

4.2.2 | Bioremediation through introduced flora

Plants and aquatic animals have been cultured together for centuries in both freshwater and brackishwater systems.[90,91] It provides the advantages of better nutrient utilization, possible income from secondary crops, as well as pest and disease control. Incorporating plants into freshwater fish and crustacean production systems has been shown to improve water quality and reduce nutrient concentrations.[92,93] For example, an Australian native lotus (*Nelumbo nucifera*) was studied for its effectiveness in bioremediation of freshwater barramundi pond discharge, removing an extra 15% of TN over treatments without the native lotus.[94]

Several species of marine macroalgae have been studied for their potential to phycoremediate aquaculture production pond discharge. This includes the green algal species, *Caulerpa* sp.[95,96] and *Ulva* sp.,[97–100] as well as the red algal species, *Gracilaria* sp.[101–103] While some have potential to provide a commercial return, their suitability and performance needs further assessment. Paul and De Nys (2008)[95] concluded that while *Caulerpa* sp. had promise for use in pond aquaculture systems, the competition from filamentous algae (*Cladophora* and *Chaetomorpha* sp.) meant that *Caulerpa* could not be used in treatment ponds. Another study showed that nitrogen uptake rates of *Ulva rigida* were relatively high (equivalent to 5.5 kg N ha^{-1} d^{-1}) under controlled conditions, but results in treatment ponds were less impressive (240 g N ha^{-1} d^{-1}).[104] *Ulva ohnoi* was identified as an ideal target species for phycoremediation of aquaculture pond discharge, due to its fast growth and geographical distribution.[105] This species tolerated temperatures from 18 to 34.5°C but the optimal temperature was 28°C.[106] Identifying algal species that occur naturally in the climatic region of interest may be a first step in determining their suitability for nutrient removal, however, this does not guarantee success in real-world treatment systems.

Beyond studies and development at a pilot scale, phycoremediation has so far not been globally adopted by the aquaculture industry.[107] This is despite many years of research, which suggests that it does not currently provide a practical and cost-effective solution for aquaculture farmers. One contributing factor may be the low economic value of the algae. For example, cultivation of the red alga *Asparagopsis* sp. has been investigated as a crop to reduce nutrient loads from aquaculture.[107] Although this species has potential pharmaceutical applications[108] and can reduce methane production from cattle by 80%,[108,109] there is no evidence to date that it is cost effective to grow this species in a treatment system.

4.2.3 | Bioremediation through introduced fauna

Introduced filter feeding organisms, like oysters and mussels,[110–113] as well as planktivorous or detritivorous species of fish and crustaceans[114,115] have been investigated for their potential to utilize waste nitrogen from pond aquaculture. Bivalves remove microalgae and other particulates, including inorganic matter, from the water column. Inorganic matter is agglomerated into pseudofaeces which settle relatively easily. However, if the suspended solids load is too high, filtration is suppressed, and growth and survival of the bivalves may be compromised. Nitrogen removal efficiency is not necessarily high, as bivalves retain only about 25% of the nitrogen consumed,[116] the remainder may be excreted either as inorganic nitrogen or organic nitrogen in urine and faeces. Sydney rock oysters (*Saccostrea commercialis*) have been shown to decrease the TN concentration of shrimp pond discharge water by about 33%, but increased the proportion of DIN in the TN from 9% to 46%.[101] Building on these results, a pilot scale system initially showed an improved efficiency of nutrient removal by the oysters, but the suspended solids load in the discharge caused fouling of the oysters, and subsequent mortality.[111]

Black clams (*Chione fluctifraga*) have been used for the bioremediation of semi-intensive shrimp pond discharge water.[117] The water was treated through either a settlement tank or a settlement tank stocked with clams. While both treatments significantly reduced the amount of total ammoniacal nitrogen in the discharge water, the clams removed significantly more. However, TN was not significantly reduced by either treatment. The authors concluded that the black clam offered a moderate capacity to bioremediate shrimp pond discharge. Van Khoi and Fotedar (2012)[118] found that the density of blue mussels (*Mytilus edulis*) influenced the effectiveness of bioremediation. At higher mussel densities there was a modest (5%) reduction in TN concentration, although both orthophosphate and total phosphorus increased. This increase in phosphorus was attributed to excretion by the mussels. In another study, banana shrimp (*Penaeus merguiensis*) stocked at a low density (1.1 to 5.5 m^{-2}) into treatment ponds in a *P. monodon* farm were used to examine the utilization of waste nutrients.[115] Penaeid shrimp, in particular *P. merguiensis*, consume microalgal detritus, microbial flocs and meiofauna as part of their natural diet,[119,120] so are a good candidate for converting some of the organic nutrients in settlement ponds into biomass. However, the system was not effective as the biomass of *P. merguenisis* harvested from the settlement ponds was lower than anticipated, and rather than reducing TN output from these treatment ponds, the loads were slightly higher in the latter part of the study.

Studies on the co-culture of tilapia and shrimp has shown potential for economic and production benefits.[121–123] The increase in overall nutrient retention by the harvested fish and shrimp provides an advantage in reducing the amount of nutrient in the water column that may be released into the surrounding environment. A study in tanks without water exchange, showed an increase in nitrogen retention at harvest from 27% for the shrimp monoculture to a combined retention of 36.0%–49.5% for the co-cultured treatments.[124] In the same study, phosphorus retention was similarly improved from 8.9% in the shrimp monoculture to 14.2%–26.5% in the fish-shrimp treatments. The final concentration of TN of the culture water in the shrimp monoculture was 19 mg L^{-1} with the fish-shrimp treatments being lower at 13 to 17 mg L^{-1}. Overall, bioremediation offers only a moderate capacity for discharge water treatment. Since effectiveness is influenced by several factors, considerable time and resources are needed to ensure that the approaches outlined above remain effective within farms.

4.3 | Wetlands

Natural and constructed wetlands have the potential to significantly reduce nutrient loads from aquaculture. They are already used for the treatment of municipal, industrial and agricultural wastewater and catchment runoff.[125] In both fresh and saltwater aquaculture, they may be used as a final polishing step before water is recirculated back to production units or prior to release into the surrounding aquatic environment.

Constructed wetlands are typically shallow artificial wetland systems supporting rooted vegetation, where waterflow can be controlled, so that natural plant and microbial processes can reduce nutrient loads. There are different designs categorized by both the path of water flow (e.g., vertical, horizontal, free water surface, subsurface flow) and vegetation.[126] The design, construction and choice of vegetation can influence the efficiency of nutrient removal. Wetlands that are flooded, planted basins which allow a shallow layer of water to flow across the surface of the soil are known as free water surface (FWS) wetlands (Table 2). Horizontal subsurface flow (HSF) wetlands are designed to keep the water level below the surface while also supporting vegetation. Vertical subsurface flow (VSF) wetlands are designed to operate with a pulse flow of input water which floods the surface of the wetland, then percolates through the substrate to be collected from the bottom of the wetland basin. Vegetation is very important to vertical flow wetlands and may include mangroves, emergent vegetation such as reeds, and submerged aquatic vegetation, depending on the salinity and substrate in the wetland.

Constructed wetlands are generally considered highly efficient in removing particulate organic matter, suspended solids and microbial pollutants, but less efficient at removing nitrogen and phosphorus.[127] In aquaculture, constructed wetlands (usually FWS) have been investigated for treating fish and crustacean discharge water. While most of the focus has been on freshwater or low salinity discharge, there are some studies using brackish or seawater. Generally, constructed

TABLE 2 Basic categorization of constructed wetlands.[126]

Flow category	Construction and operation	Removal efficiency and processes: Solids/Organics	Nitrogen	Phosphorus	Role of vegetation (e.g., Mangroves, reeds, macroalgae, water plants)
Free water surface (FWS)	Soil based. Flooded planted basin. Water flows across the soil surface	High. • Settlement and detention	Moderate • Nitrification/ denitrification. • NH_3 volatilization.	Moderate slow—settlement and soil adsorption.	Contributes to nutrient removal but usually retains <10% N input load. Needs to be harvested regularly. Algal growth promotes NH_3 volatilization (pH >8).
Horizontal subsurface flow (HSF)	Materials to allow high hydraulic conductance. Water flows beneath the substrate surface	Pre-treatment is required to reduce load and maintain flow. • Very effective filter, but clogs easily if no pre-treatment	Moderate • Nitrification/ denitrification. • May be restricted through low oxygenation. • NH_3 volatilization ineffective.	Low due to poorer sorptive capacity of construction materials.	May contribute if harvested regularly • but usually retains <10% N input load.
Vertical subsurface flow (VSF)	Pulse flow (empties before next pulse of inlet water). Water floods surface and percolates down through substrate. Materials to allow percolation. Complex to design, operate and maintain.	Very effective. • Filtration	Moderate • NH_3 volatilization. • Promotes nitrification but denitrification limited by fewer anoxic areas.	Moderate—depending on construction materials.	Very important to: • reduce clogging. • provide bed stability. • provide aerobic zones for microbes.

Note: Wetlands may be further categorized based on the choice of vegetation used.

wetlands take time (at least 60 to 90 days) to establish before there is effective nutrient removal.[128,129] Once established, the reported removal efficiency for TN reduction has been shown to be highly variable, that is, −27% to 64%.[125,128,130,131] Like settlement ponds, accumulation and subsequent remineralization of nutrients from organic matter (including leaf litter and other dead material from within the wetland itself) can lead to increases in the dissolved inorganic nutrient concentration of the outflow. Wetlands have the advantage of providing habitat for birds and other animals, but this can also import nutrients to the wetland and increase the nutrient load in the outflow.[132]

In constructed wetland systems, the vegetation helps oxygenate the root zone to facilitate microbial and chemical nutrient transformations, but it is the microbial community, rather than the vegetation, that is more important as a direct sink for nutrients. Erler et al. (2010)[133] found that in a constructed wetland, only 7.4% of the nitrogen input was retained in the plant material, while it was estimated that denitrification resulted in about 41% of the nitrogen input being lost to the atmosphere as N_2. Salt tolerant plants (halophytes) and marine algae can provide similar benefits to freshwater plants in treatment systems for saltwater aquaculture, but the range of plants that can be used is greatly reduced. Seagrass for example, while obviously suited to a marine environment, does not survive the higher TSS concentrations in aquaculture treatment systems, resulting in lower light available for photosynthesis, as well as causing fouling of leaves. In coastal farms, salt tolerant plants like mangroves and the mangrove fern (*Acrostichum aureum*) have been used to vegetate constructed wetlands. However, not all mangroves have the same effectiveness. A comparison of different mangrove species in an aquaculture system showed that the river mangrove (*Aegiceras corniculatum*) was most tolerant to the conditions, while the orange mangrove (*Bruguiera gymnorhiza*) had the fastest growth rates.[134] However, the ability of the orange mangrove to remove nutrients from the water column was markedly lower than for the river mangroves.

While wetlands can be effective at a pilot scale, there is little information regarding the effectiveness of farm scale treatment wetlands. Scaling up wetlands to provide sufficient HRT for the large volumes of discharge water from pond aquaculture is challenging. Schwartz and Boyd (1995)[130] estimated that a 1 ha (15 ML), freshwater catfish pond which was drained over 7 days through a wetland with a four-day HRT, would require 2.7 ha of wetland. Draining the same pond in 1 day would increase the area required to 18.75 ha.

Wetlands and constructed wetlands are considered land-intensive, low-cost systems, but they do require maintenance and monitoring, for example, removal of deposited sludge and sediment.

Common issues identified in a survey of agricultural and municipal wetland treatment systems in New Zealand include: sparsely vegetated areas due to plant mortality promoting short-circuiting and reduced sedimentation; poor inlet/outlet maintenance leading to scouring and resuspension of solids and clogging; and challenges with operating outside the designed water depth.[135]

4.4 | Integrated production systems

Integrated aquaculture production was historically differentiated from polyculture as a concept that involved farming of terrestrial and aquatic species together, but this term has been redefined in several ways over time.[136] Integrated multi-trophic aquaculture (IMTA) is farming species from different trophic levels within the same system or near proximity. More simply, it is combining the cultivation of fed species, and species that utilize the waste nutrients from that production.[116,136] IMTA uses the waste from fed aquaculture as a source of nutrient for the extractive organisms to exploit and recycle into a productive resource. These extractive organisms may be herbivorous/detritivorous/planktivorous fish or shellfish which can utilize the organic particulate nutrients, and aquatic plants and macroalgae which extract the inorganic nutrients. The term—integrated aquaculture—will be adopted here to cover all these integrated systems.

Integrated aquaculture has been studied using, for example, open-water cage culture,[137] land-based pond culture,[138] and recirculating systems.[96] One study of a model system with integrated fish, bivalve and macroalgae estimated that 63% of the nitrogen input as feed would be harvested in the combined yield from the three components, 33% would be sedimented, with only 4% being discharged.[97] The effectiveness of the macroalgae unit for nutrient mitigation was reliant upon a range of design factors, algal stocking density and nutrient load. While these factors may be controlled, other environmental conditions, such as weather, climate and pests, will also influence the performance of the unit.[99]

A reduction in the price of shrimp and health challenges faced by the sector has led to the adoption of integrated tilapia and shrimp production in some areas.[121,122] Growing tilapia with shrimp offers benefits through a reduction of harmful bacteria (e.g., *Vibrio harveyi*) and more stable algal blooms within the ponds.[121,139] There is some evidence that the productivity of the shrimp is enhanced in polyculture compared with monoculture,[121,122] although Yuan et al. (2010)[124] found that increased size and density of the fish used negatively impacted shrimp production.

While there are benefits in integrated production systems like this, the optimal stocking density of each species may be reduced in order to manage oxygen demand within the system.[121] The increased complexity of managing these systems with species that have different grow-out periods may result in farmers returning to monoculture as prices improve and disease challenges are reduced or controlled through other methods. The reality is that while integrated aquaculture has been the subject of global research efforts and has shown potential for bioremediation capacity, there has been limited commercial success.[140]

4.5 | Options combining physical, chemical and biological treatment

Another concept that has been examined is the combination of physical, chemical and biological treatment for nutrient reduction. This approach is commonly used in municipal wastewater treatment systems and has also been adopted in tank-based RAS.[141–144] There have also been some attempts at combining various elements into treatments systems for pond-based aquaculture. Castine et al. (2013)[141] presented a conceptual model of a treatment system for a hypothetical 100 ha shrimp farm. This model drew upon the published performance of different technologies from aquaculture and municipal water treatment. They used a combination of physical and biological treatment systems, but unfortunately the model only accounted for about 43% of the TN input in the nutrient budget presented.

These integrated systems rely on a combination of component units that would each have a particular role within the system. While not an exhaustive list, some of these components may include:

4.5.1 | High-rate algal ponds

High-rate algal ponds (HRAP) are shallow, open raceway ponds with circulating water which are used to transform nutrients into microalgal biomass.[145] The ponds are designed to maximize exposure to solar radiation and nutrients to optimize microalgal productivity. Nitrogen removal in these ponds is mainly through uptake of DIN by microalgae, although there can be some pH-dependent ammonia volatilization and limited nitrification by microbes. While microalgae are efficient at converting the DIN into biomass, the nitrogen cannot be removed without harvesting the algae. Flocculation is a common method but generally requires the addition of metal salts, clays or polymers to promote aggregation (ballast flocculation). Harvesting, whether by flocculation or dissolved air floatation, can contribute 20%–60% to the total cost of biomass production.[146] More recently, bioflocculation using bacteria, fungi and other organisms has been investigated as an alternative.[145–147] The costs and logistical challenges of harvesting microalgae has led to the development of systems using macroalgae like *Ulva*. However, these systems require a reduction in the microalgal biomass in the pond discharge prior to treating the water with *Ulva* in order to reduce fouling of the plant thalli and shading of the macroalgae. Pre-treatment of discharge water is also important prior to entering HRAP to remove other suspended particulate material, and to remineralize organic nitrogen.

4.5.2 | Physical filtration

Sand filtration has been investigated as a treatment measure for shrimp pond discharge when water from the pond was exchanged at 5% d^{-1}.[148] The design required an area of about 6% of the production pond. While it did reduce the TSS in the outflow water, the organic load removal was lower than expected, and DIN levels often increased via remineralization of the organic matter trapped by the filter (which is an advantage if used as a pre-treatment before an HRAP). The beds were also prone to clogging. To alleviate this issue, Palmer (2010)[149] used a polychaete worm-assisted sand filter design to remove solids and nutrients from shrimp pond discharge. The sand beds were populated with inter-tidal polychaete worms (*Perinereis helleri*) to consume the organic matter and help prevent clogging. The results showed that while percolation rates were maintained for about a week, the rates slowed after this period as the rate of organic matter accumulation on the surface of the filter overcame the ability of the worms to clear the filter. TN and TP reduction was low and inconsistent, so commercial application of this technology may be limited.[150]

4.5.3 | Denitrification bioreactors

Denitrification bioreactors have been used by the wastewater treatment industry for many years to remove nitrogen from wastewater. There is also increasing interest in the use of denitrifying bioreactors in treating agricultural runoff which contains relatively high nitrate concentrations.[151] These bioreactors promote anaerobic conditions and use an added carbon source, for example, woodchips, to stimulate denitrification and subsequent release of nitrogen gases (NO, N2O and N_2). The decay rate of softwoods was found to be faster than hardwoods which provided more rapid benefits. However, there may be issues with longevity of the processes, and performance related to nitrate reduction over time. As with most treatment systems, higher inlet nitrate levels (>10 mg N L^{-1}) increased the efficiency of nitrate removal.[151] Nitrate removal rate is also affected by the HRT and the age of the bed. Bioreactors with a carbon source bed that is in its first year of use will have a higher nitrate removal rate than older beds. Although the removal rate appears to stabilize after this first year, monitoring of older beds is required to maintain efficiency.

Denitrifying bioreactors have been investigated in pond systems but they are more commonly used in RAS where the stocking density of animals and the nutrient concentrations are higher than in flow-through systems. This makes this treatment option more efficient and cost-effective. Von Ahnen et al. (2016)[152] found 11 days was needed to establish the biota in a reactor treating trout farm discharge (5.6 mg nitrate-N L^{-1}). The establishment phase for another study treating trout RAS discharge was 162 days, although these units were designed for a much higher concentration of input nitrate (60 to 80 mg N L^{-1}).[153,154]

Christianson et al. (2016)[153] reported very high nitrate (70%–100%) and TSS (>90%) removal once bioreactors were established, using inflow nitrate concentrations of 25 to 80 mg N L^{-1}. However, as the experiment progressed, the bioreactors experienced some clogging and changes in the flow within the reactors. Therefore, these units are likely to need to be preceded by filtration to remove most of the solids. During periods of low nitrate inputs, the anaerobic condition may result in the production of undesirable compounds, like methane and hydrogen sulphide, so this needs to be considered in the design parameters.[151]

4.5.4 | Coagulation and flocculation

Coagulation and flocculation can be used to reduce the suspended solids load in water by encouraging the aggregation of particulates, increasing the rate of settlement. Coagulation refers to the destabilization of a suspension and relies on neutralizing the charge on these particles with ions of the opposite charge. This has typically been achieved through the addition of aluminium or iron salts.[155] Flocculation refers to the process by which these particles are encouraged to form aggregates.[88] Flocculation aids, including synthetic or natural polymers, may be added to enhance this process.[87,156]

Chemical coagulation and flocculation are not favoured in the treatment of aquaculture production pond discharge due to the relatively low concentrations of nutrients and solids in the discharge.[88] The addition of chemical coagulants and flocculants may also limit the options for disposal or reuse of the resulting sludge. The alum sludge from municipal water and wastewater treatment has been shown to contain significant amounts of aluminium, of which around 10% was in bioavailable forms posing an environmental risk.[157]

One product used as a flocculant for microalgae is chitosan which has been shown to remove 50% to 85% of the microalgae from *P. vannamei* culture tanks. This efficiency is maintained at chitosan addition rates of 40–80 mg L^{-1} and at pH range 7–9, post addition.[87] However, operational costs for this approach are high, including costs of the chitosan, as well as acetic acid or sodium hydroxide needed to adjust the pH.

Electrochemical techniques are also used to treat industrial, municipal and agricultural wastewater.[88,155,158] These involve direct reactions at the anode, or reactions in solution with ions supplied by the electrode.[155] Electro-oxidation, electro-flotation and electro-coagulation are established methods for various treatment purposes.[159] Electro-oxidation (EO) can be achieved through direct oxidation of organic compounds at the anode, or indirectly through the creation of oxidizing agents, such as chloride ions or hydrogen peroxide in solution.[159] Electro-flotation (EF) removes pollutants through the creation of tiny bubbles of hydrogen and oxygen gases which float the pollutants to the surface. Electro-coagulation (EC) generates coagulants in situ using sacrificial iron and aluminium electrodes, releasing the metal ions from the anode and hydrogen gas from the cathode.[155,159]

In aquaculture, EC has been studied as a potential treatment method in recirculating systems,[158,160–164] and for harvesting of microalgae.[165] The advantages of EC over chemical coagulation are: addition of chemicals is reduced; flocs are larger and more easily filtered; less sludge is produced, it settles more quickly and is more easily dewatered.[155,166] Igwegbe et al. (2019)[160] used EC to treat water collected from a freshwater fish pond in the laboratory and showed that EC reduced TSS (>90%), nitrate (about 89%) and phosphate (46%) after flocculation and settlement. However, in a *P. vannamei* system, treating discharge water with EC followed by microfiltration only reduced nitrate by 19%.[162]

During the EC process some of the ammonia and nitrite will be converted to nitrate,[167] so nitrate should not be examined in isolation.[162] The greatest reduction in TN that was measured with this EC system was close to 59% when combined with filtering at a pore size of 45 μm. When the filter pore size was increased to 75 μm the TN removal rate was reduced to around 25%. There are several factors which affect the efficiency of EC including: electrical conductivity, pH, choice of electrodes, temperature, water flow rate and HRT.[162,168] Therefore, comparison between reported results is difficult. Bhatt et al. (2023)[158] studied an EC system to optimize the parameters for treatment of water from shrimp production. They found that iron electrodes were superior to aluminium and reported that using iron electrodes, the reduction in nitrate was 67% after 60 min while total dissolved nitrogen (TDN) was reduced by 92% after 20 min. The optimal pH for TDN removal was 5 and an operation time of 60 min, while the highest phosphate removal (82%) was at pH 5 but for only 20 min. In contrast, the study by Xu et al. (2021)[162] used a combination of iron and aluminium electrodes with an operation time of just 4.5 min at the unattenuated pH (7.12) of the water.

While there has been some attention paid to the use of EC as a method of treating aquaculture production discharge in recirculation systems, applying this to the high volumes discharged from pond aquaculture may be a challenge.[168] This technology had demonstrated effective at a laboratory scale, but scaleup is still needed in order to deliver practical benefits.

4.6 | Biofloc pond systems

Traditional semi-intensive and intensive pond production systems use water exchange to control the impact of feed inputs and waste products on the water quality but there are circumstances where drawing in clean water from the adjacent waterways is not possible or desirable.[37] Biosecurity is one of the strongest drivers for the adoption of reduced water exchange regimes, which also reduces the nutrient contribution from intake water.[169,170] Devastating shrimp disease outbreaks in Asia and the Americas[171,172] hastened the development of minimal or zero water exchange systems for shrimp production to reduce the risk of infection from intake water.

Biofloc pond production systems are systems with low or no water discharge which rely on microalgae and microbes to control toxic ammonia and waste accumulation within the production pond.[170] Managed correctly, the high biomass of these microalgae and microbes will clump together, along with waste products, to form a flocculated material, known as biofloc.[43] This material is available to fish and crustaceans as a beneficial feed source, recycling nutrients that would otherwise have been unavailable to the production animals. Approximately 18%–29% of the nitrogen retained by shrimp (*P. vannamei*) in a biofloc pond was found to be derived from the flocculated material.[173] A similar retention (25%) was measured for tilapia grown in a biofloc system.[174] Biofloc has also been shown to significantly improve the retention of feed protein in *P. monodon* when using lower protein (25%) feeds.[175] Bioflocs have also been shown to promote processes beneficial to ammonia reduction via conversion to nitrate, increasing the efficiency of denitrification, and hence nitrogen removal from ponds.[43]

The conversion of waste nitrogen into biofloc requires adding carbon sources to maintain a high carbon to nitrogen ratio (12–20:1 initially and 6:1 with ammonia once established) fueling growth of microbes which enhance the processing of nutrients. There is some evidence that the nutritional benefit derived from the biofloc may allow the protein content of the pelleted feed to be reduced without compromising shrimp growth.[56,175] An Australian study examined the modified application of this technology to commercial production of *P. monodon* showing that production increased from 8 t ha^{-1} in an open water exchange system to 12 t ha^{-1} in the biofloc system.[176] Additionally, the authors identified a 77% reduction in nitrogen discharge per t of shrimp produced.

Maintaining sufficient water circulation and dissolved oxygen concentrations is important to the success of biofloc systems. Water circulation encourages aggregation of the particles to form the biofloc. The systems have a high biological activity, which in turn creates a high demand for oxygen, so mechanical aeration needs to be sufficiently high. The resulting water movement erodes earthen ponds, so ponds are usually fully lined to prevent this. These factors all increase the input costs for production, and the increased biological biomass and oxygen demand requires more stringent monitoring and management, but also increases the risk of losses should elements of the system fail.

Biofloc technology has been most widely adopted for tilapia production, and intensive (yielding 6–10 t ha^{-1}) and super-intensive (70–100 t ha^{-1}) production of *P. vannamei*. To take full advantage of the system, the production animals would utilize the biofloc as a supplementary feed source. Animals must also be able to tolerate: high stocking densities; dissolved oxygen concentrations as low as 3–6 mg L^{-1}; and settling solids (floc) concentrations of 10–15 mL L^{-1}.[4] Biofloc research is being conducted into the production of a variety of freshwater cyprinids[177-184], catfish[185–187] and other omnivorous fish species.[188–190] Based on encouraging preliminary results, further trials have been recommended for aquaculture of eels in biofloc systems.[191]

Biofloc systems may be beneficial even if animals cannot directly utilize the biofloc as a feed. There may be benefits from processing nutrients into forms that more readily settle or enhance denitrification, and secondly through improved survival and growth from a health and biosecurity perspective.[192–194] A recent small-scale study has used this system for growing barramundi in freshwater.[195] Although there appears to have been no difference in the growth of the fish with or without floc, the ammonia levels in the culture tanks were reduced by 15% to 75% indicating that the biofloc system was able to control water quality and did not harm the fish.

Due to the capacity of biofloc to alleviate ammonia stress, intensive nursery production is an active research area for a range of omnivorous finfish.[196–199] However, studies with carnivorous species continue to show disappointing survival and growth in floc nursery systems.[200–204] However, species which are unsuited to the biofloc system could still derive benefit from stand-alone production of biofloc which can be included in pelleted feeds.[205,206]

While biofloc systems have reduced water exchange through the production cycle, they are not necessarily zero discharge systems, with ponds often being harvested through complete draining. A corollary of the high-energy input needed to suspend the floc is that this material promptly settles in a sedimentation pond. Production of bioflocs is therefore beneficial for the efficiency of nitrogen removal in sedimentation ponds.

4.7 | Recirculation systems

Aquaculture pond discharge is characterized by large volumes and relatively dilute nutrient concentrations compared with other point source discharges, for example, sewage treatment plants. Using approaches to concentrate the nutrient load may make treatment systems function more efficiently, as has been demonstrated for the biofloc systems. However, there are also options to have outdoor recirculating tank or pond systems without bioflocs, using treatment of the recirculated water prior to its return to the production units. There are examples of production of either fish or crustaceans under reduced or zero exchange conditions.[98,125,207,208]

A pilot scale, earthen, recirculation pond for low salinity *P. vannamei* production was developed along with a constructed wetland, with a wetland to production area ratio of 0.086.[125] The wetland had 28% of it's area as a floating aquatic plant basin flowing into a subsurface flow constructed wetland. Once water had passed through the wetland it was returned to the pond. While suspended solids were reduced by 60%, and both nitrate and TP decreased slightly through the treatment system, the TN and ammonium concentrations increased. These results contrasted to previous work which used an FWS constructed wetland, and a subsurface flow constructed wetland in series to treat output from a low-salinity recirculating tank production unit culturing the same species of shrimp.[208] In that study, the wetland system reduced the influent concentrations of suspended solids (71%), ammonia (57%), nitrate (68%) and phosphorus (5%).

Water recirculation within farms increases the risk of disease and harmful algal species spreading through the farm. Therefore, treatments such as drum filtration, ozonation and in-pond sludge removal can be used to mitigate some of the risks. Ozonation is used in water treatment for disinfection, inactivation of viruses, and microflocculation for removing suspended solids and algae. Although the equipment and power requirements add significant costs to production, ozonation can be used in recirculation systems to disinfect the water for biosecurity purposes. However, it may also play a role in transforming and removing some forms of nutrients. For example, Sandu (2004)[209] investigated the effects of ozonation on settled discharge in a freshwater fish RAS. The author determined that ozonation caused foaming which removed total solids by about 25%. After 30 min of ozonation, the total Kjeldahl nitrogen concentrations were also reduced by 72%–94%. This was determined to be primarily organic nitrogen, with ammonia increasing by 13%–45%. Nitrite was totally oxidized to nitrate within the first 9 min of treatment.

5 | CONCLUSIONS

This review examined the benefits and limitations of options to reduce nutrient waste from aquaculture ponds. There are low-cost approaches to treatment, such as settlement ponds, but they are typically inefficient at reducing nutrients. Biological treatment using plants and animals typically results in an increased degree of unreliability, and in some cases, requires considerable additional land area. Technologies used in treating wastewater are currently too expensive to be used across the aquaculture industry. The key findings are that there is a lack of inexpensive and simple solutions for managing nutrient discharge from ponds. However, use of recirculation systems provides a mechanism for increasing nutrient concentrations, provided farm designs and operations can be modified. These higher concentrations can be more efficiently and cost-effectively processed using more techologically advanced treatment methods. In the case of implementation of biofloc systems, they may provide both a supplementary food source for animals and an in-situ nutrient treatment capacity. Overall, there is scope to improve treatment of waste nutrients, but modifications to many production systems are needed to achieve this, as well as an assessment of the cost-effectiveness of the various options.

AUTHOR CONTRIBUTIONS

Simon Tabrett: Writing – original draft; conceptualization; writing – review and editing. **Ian Ramsay:** Conceptualization; funding acquisition; writing – review and editing; resources; validation. **Brian Paterson:** Writing – review and editing. **Michele A. Burford:** Conceptualization; investigation; writing – review and editing; methodology; project administration; supervision; funding acquisition.

ACKNOWLEDGEMENTS

This project was supported by Queensland Department of Environment and Science, and Griffith University. We wish to thank the Australian Prawn Farmers Association, and its members, and the Australian Barramundi Farmers Association, and its members, for their input to enhance the information in this manuscript. Open access publishing facilitated by Griffith University, as part of the Wiley - Griffith University agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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How to cite this article: Tabrett S, Ramsay I, Paterson B, Burford MA. A review of the benefits and limitations of waste nutrient treatment in aquaculture pond facilities. *Rev Aquac*. 2024;16(4):1766-1786. doi:10.1111/raq.12921