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Original Research Article

The Importance of Ammonia Removal Process in Aquaculture Systems — Towards Improving Malaysian Aquaculture Production

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Abstract: Due to natural resource limitations, fish production must sustainably increase. Rather than adding more areas and water to increase fish production, increased intensity of production per area is a more appropriate method. To increase production intensity, one of the main priorities that has become a continuous challenge during farming operations is maintaining good water quality, the first defence mechanism to secure fish growth and health in aquaculture systems. Other inventions related to fish husbandry, feed technology, and health, such as vaccines and probiotics development, are tested and implemented in the production systems, further emphasising the importance of water quality. Water quality determines system carrying capacity, further determining the maximum production a system can achieve. Ammonia is one of the most harmful wastes that must be managed in an aquaculture system. The capability of managing ammonia could increase systems' carrying capacity tremendously, especially in super-intensive systems. This article discusses available methods of ammonia removal applied in biofloc technology, recirculating aquaculture system (RAS), aquaponic system and green water technology. The critical water quality parameters to be monitored for each method are briefly reviewed. In methods like these, biological processes for ammonia removal are pivotal. Therefore, adopting the appropriate engineering approach to support the biological processes is essential to improving ammonia removal performance.

Keywords: Recirculating aquaculture systems; biofloc technology; aquaponic system; green water technology; engineering approach, ammonia removal

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1. Introduction

Sustaining the long-term production and supply of food fish from aquaculture is significant, and the ongoing challenge is to reduce dependency on captured fisheries. Aquaculture is the fastest food-producing sector in the world, accounting for 49% of the total fish production, and the remaining 51% is contributed by capture fisheries production (FAO, 2022). Over the years, catch levels from capture fisheries production remain close to sustainable levels, with an increase of 14% from 1990 to 2018 (FAO, 2020). However, aquaculture production had a tremendous rise in global production, approximately 527% from 1990 to 2018 (FAO, 2020). This trend reflects the increase in the world food fish consumption, that has reached 20.5 kg per capita in 2019 (FAO, 2022). All the facts and figures predict that the aquaculture sector will be the primary driver of the world fish supply. Malaysia supports the aquaculture sectors in which the National Agrofood Policy 2021-2030 (NAP 2.0) emphasizes that fish production must be increased at self-sufficiency level (SSL) and to increase the income of the farmers' involved. This is in line with the Sustainable Development Goal 2- Zero hunger, where efforts for food security and aquaculture sustainability will continue to be the focus by improving aquaculture management strategies and the livelihoods of millions of small-scale aquaculture farmers.

Meanwhile, aquaculture is one of the major food producers in Malaysia, with an annual value of RM3.06 billion (DOF, 2019). Aquaculture production in Malaysia remains stagnant as aquaculture production has only increased by approximately 10.5% from 2008 to 2018 (DOF, 2019). It is estimated that the food fish consumption in Malaysia has reached 56.8 kg per capita, whereby approximately 73% of the total fish production was contributed by the capture fisheries sector, valued at 1.4 million tonnes (DOF, 2019). NAP 2.0 targets to increase aquaculture share by the Ratio of captured fisheries landing to aquaculture landing to achieve 60:40. Generally, the aquaculture production in Malaysia is conducted in various systems, which include ponds, cages, ex-mining pools, tanks, and pen culture (Table 1). Pond culture for marine, brackish, and freshwater aquatic species contributed to the largest segment in Malaysia's aquaculture production, followed by cages, ex-mining pools and tanks. Also, a similar trend is observed for world aquaculture, where most of the production volume comes from pond systems (Bosma & Verdegem, 2011; FAO, 2016, 2022). There is growing interest in culturing fish and shellfish in indoor systems such as recirculating aquaculture systems (RAS), indoor biofloc systems, and aquaponics in Malaysia, but it is in its infancy.

The production per unit area of fish varies depending on the culture species and the production systems used. For example, tilapia production in pond systems can range from 80 to 120 tonnes ha^{-1} in intensive ponds (El-Sayed, 2006), whereas in intensive RAS, production of 1160 tonnes ha^{-1} was recorded (McGraw, 2018). Meanwhile, in Vietnam, the highest production of striped catfish (*Pangasianodon hypophthalmus*) ever recorded is between 200 – 400 tonnes ha^{-1} per 6 to 8 months in pond culture (De Silva & Phuong, 2011). In China, in intensive pond systems culturing common carp, crucian carp (*Carassius carassius*) and grass carp (*Ctenopharyngodon idella*), production of up to 30 – 40 tonnes ha^{-1} was recorded (Edwards, 2015). In Malaysia, the highest average production per unit area is achieved in the cage system (163.5 tonnes ha^{-1}), followed by the pen culture system (56.2 tonnes ha^{-1}), tanks (49.3 tonnes ha^{-1}), ponds (12.8 tonnes ha^{-1}) and ex-mining pools (6.1 tonnes ha^{-1}) (Table 1). For freshwater fish species, the most cultured fish species are freshwater catfish, which is dominated by African catfish (*Clarias gariepinus*), red tilapia (*Oreochromis* spp.) and river catfish (*Pangasius* sp.). Meanwhile, the marine species that are most cultured are white shrimp (*Litopenaeus vannamei*), seabass (*Lates calcarifer*), and snapper (*Lutjanus vitta*). This considerable production variation per unit area showed that different aquaculture practices will lead to different yields. This implies that different method would be needed for different types of system to increase aquaculture production.

Table 1. Total aquaculture production for different types of aquaculture systems

Aquaculture system	Total area (ha)	Total production (tonnes)	Aquaculture production (tonnes ha^{-1})	Top freshwater cultured fish species	Top marine cultured fish species
Pond	11,483	146,613	12.8	Freshwater catfish, red tilapia	White shrimp, seabass
Cage	288	47,074	163.5	River catfish, red tilapia	Seabass, mangrove snapper, red snapper
Ex-mining pools	3,244	19,936	6.1	River catfish	Not related
tanks	99	4,884	49.3	Freshwater catfish, red tilapia	Mud crab, white shrimp
Pen culture	13	731	56.2	River catfish	Hybrid grouper

Data adapted from the Department of Fisheries, Malaysia (DOF, 2021).

There are still setbacks in the aquaculture industry that require serious attention from the Malaysian government and industry players. Key hurdles such as adequate clean water supply, disease outbreaks, pollution and labour must be addressed to propel the industry forward. These aspects have intertwined that problem into one that would affect the other. For instance, poor water quality in a pond or cage culture system would aggravate problems for cultured fish or shellfish, such as poor growth performance, disease, and parasite outbreaks. Besides that, the traditional method of aquaculture practices in Malaysia is labour-intensive, and as such, having a labour shortage would lead to poor farm management. Furthermore, the pond system is struggling with sustainability issues such as excessive water use and discharge of aquaculture waste to the natural water bodies, which causes deterioration of water quality (Bosma & Verdegem, 2011; Hlordzi *et al.*, 2020). Due to these challenges, Bosma and Verdegem (2011) suggested that aquaculture production must be increased through the increased intensity of production per area rather than adding areas and water used for aquaculture to improve the sustainability of aquaculture activity.

The intensity of production per area can be increased by increasing the system's carrying capacity. When more fish are to be stocked in an area, more feed will be given to the system. Thus, the fish waste treatment process must be improved. Good water quality is the first defense mechanism to secure fish growth and health in aquaculture systems. Additionally, other inventions related to fish husbandry, feed technology, and fish health, such as vaccines and probiotics development, are tested and implemented in production systems, further emphasising the importance of water quality. This article focuses on ammonia removal, a critical process in aquaculture. It briefly reviews available methods for ammonia removal and essential water quality parameters to monitor. The methodology falls under the 'traditional review-narrative summary' (Grant & Booth, 2009). While not an in-depth critique, this review offers an overview of crucial concepts for ammonia removal in aquaculture systems. It aims to stimulate interest among farmers, researchers, and engineers in the current practices of ammonia removal in aquaculture production.

2. Ammonia Removal Processes in Aquaculture Systems

Aquaculture produces solid and dissolved wastes (Figure 1). Solid waste is mainly from uneaten feed and fecal matter, whereas dissolved waste is the product of food metabolism, mainly in the form of nitrogen and ammonia. The most harmful waste that the fish produce is toxic nitrogenous waste, unionized ammonia (NH_3) (Colt & Orwicz, 1991; Liao & Mayo, 1974; Tran-Duy *et al.*, 2012; Verdegem, 2013; Yusoff *et al.*, 2011). This waste is also produced by decomposing organic materials in the system, originating from fish faeces and uneaten feed. In water, unionized ammonia (NH_3) and ionized ammonium (NH_4^+) exist in equilibrium, which forms the total ammonia nitrogen (TAN) ($NH_3 + NH_4^+ = TAN$) (Sincero & Sincero, 2003; Perez-Garcia *et al.*, 2011). This equilibrium is a function of pH in the water. Unionized ammonia (which will later be called ammonia in this article) production in aquaculture can be estimated by the amount of feed given and the protein content of the feed. From the literature, it is estimated that 50% to 70% of nitrogen in the feed given becomes ammonia waste (Schneider *et al.*, 2005). Ammonia concentration below 1 mg L^{-1} should be maintained in aquaculture systems to ensure fish health.

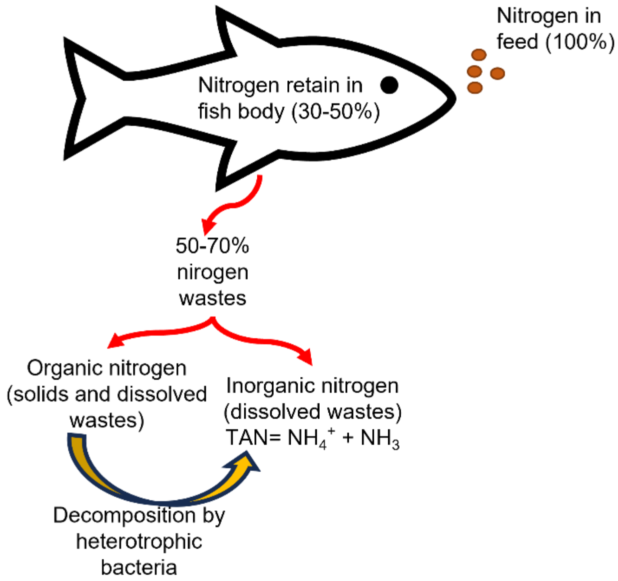

Figure 1. Nitrogen waste production by fish.

Ammonia purification can be achieved within aquaculture systems. The efficiency of the purification process can be reflected in the water exchange rate of the systems. The lower the water exchange rate, the higher the efficiency level of water purification is achieved in the system. Based on the water exchange rate, aquaculture systems can be categorized into three types of production systems: 1) flow-through system (e.g., cage and raceways), 2) semi-flow-through system or semi-recirculating aquaculture system (RAS) (e.g., ponds), and 3) RAS. In the flow-through system, the highest water exchange rate is applied (>50 m^3 kg^{-1} feed), followed by a medium water exchange in semi-RAS (3-50 m^3 kg^{-1} feed) and a minimum water exchange in conventional RAS (1-3 m^3 kg^{-1} feed) (Bregnballe, 2015; Martins *et al.*, 2010). The unit of water exchange is expressed in the volume of water per kilogram of feed introduced in the system because the amount of feed is directly proportional to the fish stocking density of the system. Minimum water exchange rate enables lower wastes discharged into the environment, higher fish production per volume of water used, higher control of biosecurity and lower reliance on the use of antibiotics (Martins *et al.*, 2010; Ramli *et al.*, 2020; Verdegem, 2013). Therefore, the minimum water exchange rate can increase aquaculture practices' sustainability and should be the main aim of aquaculture farmers. In Malaysia, the water exchange rate for aquaculture needs to be controlled since primary production is achieved in ponds and cages.

The ammonia removal processes in aquaculture systems are seen as ways to recycle water so that the water can be reused and to recycle the nutrients, especially nitrogen, to turn it into another feed source for the cultured organisms. Especially when feed costs are high, reaching between 70% and 80 % of the total farm cost (Rana *et al.*, 2009), recapturing the wastes into feed becomes essential for all farmers. In an aquaculture system, ammonia removal can be achieved using three pathways, either by assimilation by algae or plant, assimilation by heterotrophic bacteria, or nitrification process where ammonia is oxidized to nitrite and then to a less harmful nitrate by two ubiquitous bacterial groups (Ebeling *et al.*, 2006) (Figure 2). These three processes occur in aquaculture systems simultaneously. However, due to the environmental condition of the system, one process is typically found to be more dominant than the other. For example, when light is available, photosynthesis will occur. Thus, ammonia will be taken up by algae or plants.

Another example is when the carbon to nitrogen (C/N) ratio was high in water, the heterotrophic process was dominant over other processes (Rakocy *et al.*, 2004). Therefore, to improve ammonia removal in an aquaculture system, one process at a time is favoured to ease water quality management. This review will not cover other processes, such as anammox (anaerobic ammonium oxidation) (Ismail et al., 2022), since this process is still under research.

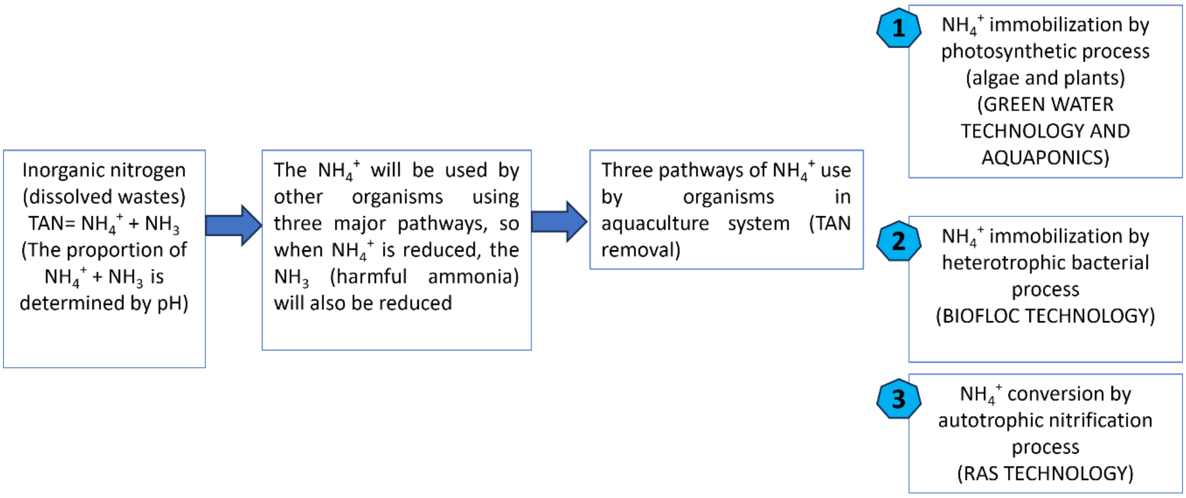

Figure 2. Total ammonia nitrogen (TAN) removal in aquaculture systems.

The following sections of this article will elaborate on how the three processes are applied: 1) heterotrophic assimilation as applied in biofloc technology, 2) autotrophic nitrification as applied in indoor RAS technology, 3) assimilation of ammonia by algae as applied in green water technology, and 4) assimilation of ammonia by plant as applied in aquaponic system. Firstly, the process mechanisms will be elaborated. Secondly, important water quality parameters that controlled the process will be discussed. Thirdly, the methods for monitoring and controlling water quality parameters will be included briefly. Table 2 summarizes the key points discussed in this chapter.

2.1 Biofloc Technology

Biofloc technology is generally applied in pond and tank systems to culture fish and shrimps (Figure 3). Heterotrophic bacterial growth is highly dependent on pH, alkalinity, temperature, oxygen, ammonia, and salinity, and this process is further enhanced by the addition of external carbon sources such as tapioca starch to increase carbon (C) content in the system (Ebeling *et al.*, 2006). A C/N ratio of 12/1 – 20/1 is vital for stabilising heterotrophic microbial communities (Emerenciano *et al.*, 2017; Jamal *et al.*, 2020). The most significant advantage of biofloc technology is that most nitrogenous wastes are captured into bacterial bioflocs, which may become natural feed for cultured organisms and improve water quality (Crab *et al.*, 2012). For feeding purposes using bioflocs, the size of flocs is essential based on the stage of the culture species: the adult stage will require larger bioflocs size than the juvenile stage (De Schryver *et al.*, 2008). According to De Schryver *et al.* (2008), power input between 0.1 to 10 Wm-3 through water mixing generally provides a flow regime supporting the formation of natural bioflocs. It was reported that at least 20 to 29 % of nitrogen waste could be captured into bioflocs and consumed by the culture species (Emerenciano *et al.*, 2017). One of the hurdles to applying this technique is the high turbidity in the culture system. Large quantities of suspended particles may cause irritation and clogging of the gills, leading to secondary diseases or death. One study suggests that turbidity between 400-800 mg/L can be applied to keep ammonia removal at a high rate and keep the turbidity level safe for cultured Litopenaeus vannamei (Schveitzer *et al.*, 2013). This study has proven that turbidity level significantly correlates to total suspended solids (TSS). However, the C/N ratio of the water culture cannot be directly indicated by turbidity or TSS level.

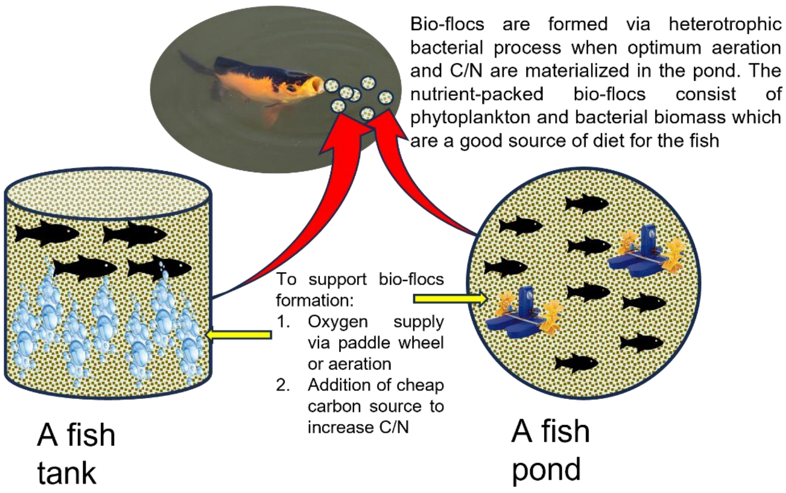

Figure 3. A biofloc system is a stand-alone fish tank or pond.

Fish excrete wastes that have high nitrogen but low carbon content. To create the bioflocs via the heterotrophic bacterial process, a high C/N ratio (between 10-20) of culture water is needed. Therefore, a cheap carbon source is added to increase the C/N ratio. Additionally, oxygen is supplied through aeration or a paddle wheel to support the process.

In the biofloc technology, three parameters are identified as the most important to be controlled: dissolved oxygen (DO) of between 4.0 to 6.0 mg L^{-1} to support fish and heterotrophic bacterial growth (Zhao *et al.*, 2012), turbidity of water at the level 400 to 800 mg L^{-1} and C/N level between 10 to 20 (Liu *et al.*, 2014; Schveitzer *et al.*, 2013) (Table 2). Digital meters that use sensor probes are commercially available for the DO and turbidity levels. Turbidity correlates with bioflocs volume, and though many studies indicated that bioflocs volume might correlate with C/N ratio (Abu Bakar *et al.*, 2015; Xu & Pan, 2013), no specific relationship can be found because fish metabolism and other environmental factors such as temperature, oxygen, carbon source influence the formation of bioflocs. For C/N level, the value of C and N must be determined separately. Test strips, color disk test kits, and digital meters are available for inorganic N measurement at the farm. For carbon level, no simple method is available at the farm site. Therefore, for research purposes, laboratory analysis using the Total Organic Carbon (TOC) method is performed for rapid and direct measurement of carbon (Abu Bakar *et al.*, 2015).

Table 2. Monitoring and controlling important water quality parameters for ammonia removal processes in aquaculture systems.

Ammonia removal process	Key Water quality parameters	Importance of the parameter	Equipment or methods for monitoring	Controlling
Biofloc system (Abu Bakar *et al.*, 2015; Azim *et al.*, 2008; Emerenciano *et al.*, 2017; Kuhn *et al.*, 2009; Liu *et al.*, 2014; Neori *et al*, 2017; Perez-Fuentes *et al.*, 2013; Ray *et al.*, n.d.; Schveitzer *et al.*, 2013)	Dissolved oxygen (mgL^{-1})	To support the heterotrophic bacterial process	Dissolve oxygen meter	Aerator (paddle wheel, nanobubbles)
	Turbidity (mgL^{-1})	To indicate solids loading in the culture water The turbidity range between 400 and 800 mgL^{-1} supported high nitrogen removal.	Turbidity meter	Installation of filtration system in culture pond or tank for solids regulation or water discharge from the system
	C/N level	To indicate the efficiency of the heterotrophic process.	Total Organic Carbon (TOC) method Inorganic nitrogen determination	Addition of a cheap carbon source in the system to increase C/N ratio (20 g carbohydrate to remove 1 g of ammonia)
	pH	To support the heterotrophic bacterial process	pH meter	pH fluctuation in biofloc systems occurs mainly due to photosynthesis and respiration. If the pH is low, adding lime can increase the pH. If the pH is high, water discharge can be done. Aeration can regulate pH levels. However, pond preparation is essential for pond systems to minimize pH fluctuation.
	The flow rate of the inlet and outlet of the culture tank	The flow rate will influence biofloc retention in the system	A high flow rate will wash away the biofloc, A slow flow rate will retain higher flocs. The flow rate between 54 and 72 litres per hour will	A pump is typically used to control flow rates.

Ammonia removal process	**Key Water quality parameters**	**Importance of the parameter**	**Equipment or methods for monitoring**	**Controlling**
			maintain an adequate level of TSS in the water column.	
Autotrophic nitrification (Attramadal *et al.*, 2014; Bartelme *et al.*, 2019; Blancheton *et al.*, 2013; Hamlin *et al.*, 2008; Ramli *et al.*, 2018; Yamin *et al.*, 2017)	Dissolved oxygen (mgL^{-1})	DO level at 5 to 6 mg L^{-1} to support the nitrification process	Dissolve oxygen meter	Aerator (paddle wheel, nanobubbles)
	pH	The nitrification process will cause pH to decrease	pH meter	pH below 7- addition of bicarbonate into the system (it is estimated that for every kg of feed given, about 0.25 kg of sodium bicarbonate is added to replace the alkalinity lost during nitrification, which causes pH decrease)
	Turbidity (mgL^{-1})	High turbidity indicates high carbon, which reduces the efficiency of nitrification.	Turbidity meter	Reducing solids in nitrification reactors, improving the performance of the solid removal process, and improving feeding activity are necessary to avoid feed loss. Besides, low feed quality may increase turbidity in a system.
Aquaponic system (ammonia is reduced in the system by autotrophic nitrification process) (Bartelme *et al.*, 2019; Buzby & Lin, 2014; Endut *et al.*, 2010; Love *et al.*, 2015)	DO, pH, and turbidity.	The exact details as explained in the section on autotrophic nitrification in RAS		
Aquaponic system (ammonia is reduced in the system by plant uptake) (Bartelme *et al.*, 2019; Buzby & Lin, 2014; Endut *et al.*, 2010; Love *et al.*, 2015)	Vegetable growth	Good growth and healthy plants are indicators that ammonia is used	The physical appearance of the vegetables could indicate good growth and healthy plants	

Ammonia removal process	Key Water quality parameters	Importance of the parameter	Equipment or methods for monitoring	Controlling
Green water or high-rate algal pond system (usually applied in pond system and tank culture system) (Deviller *et al.*, 2005; Garcia, *et al.*, 2000; Li *et al.*, 2019; Natrah *et al.*, 2014; Pagand *et al.*, 2000; Tendencia *et al.*, 2013; Tendencia & dela Peña, 2003)	Dissolved oxygen (mgL^{-1})	High DO will be observed during the day due to photosynthesis. Low DO will be observed at night because no photosynthesis occurs, and the respiration process dominates.	DO meter	Aerator (paddle wheel, nanobubbles)
	Algal biomass	Chlorophyll content	Chlorophyll meter	Shading or mixing the system can regulate the algal biomass in the case of high algae biomass. Co-culture between herbivorous and carnivorous fish can be implemented to control algal biomass in the system. In the case of low algal biomass, fertilization can be done, though this is usually done during pond or tank preparation.
	pH	High photosynthesis level		Mixing is used to avoid stratification in the system. This is usually achieved by aeration (paddle wheel or nanobubbles introduction)

2.2 Indoor RAS

An indoor RAS allows for better control of the environment and higher fish stocking density due to its ability to control ammonia levels and reduce the water exchange rate. The low ammonia level (below 1 mg L^{-1}) in RAS is achieved by using the autotrophic nitrification process. This is a two-step process where ammonia is converted to nitrite by ammonia-oxidizing bacteria, and nitrite is converted to nitrate by nitrite-oxidizing bacteria. During autotrophic nitrification, nitrifying bacteria consume carbon dioxide as their carbon source and use oxygen to grow. Therefore, as opposed to the heterotrophic process, nitrification requires a low C/N ratio, preferably between 0 and 1, as the C/N ratio at two will decrease nitrification efficiency by 70 %. (Zhu & Chen, 2001). To achieve high water purification efficiency, the RAS is compartmentalized into four main sections: fish tanks, solids removal tanks, nitrification tanks called bio-filtration tanks, and a sump (Figure 1). Water from fish tanks containing high solids and dissolved organic and inorganic carbon and nitrogen wastes will flow into solids removal tanks.

Most of the solid wastes will be trapped in the solid removal tanks depending on the efficiency of the solid removal process. Later, the clarified water with high inorganic nitrogen in ammonia will move into nitrification tanks. After nitrification, the purified water with low solids and low ammonia concentration will move into the sump and back into the fish tank. In the sump, further water purification, such as UV treatment, ozone treatment, pH control, and temperature control, may occur. Dissolved oxygen (DO) levels between 5 to 6 mg L^{-1} are maintained in the nitrification tank to support the nitrification process (Colt, 2006).

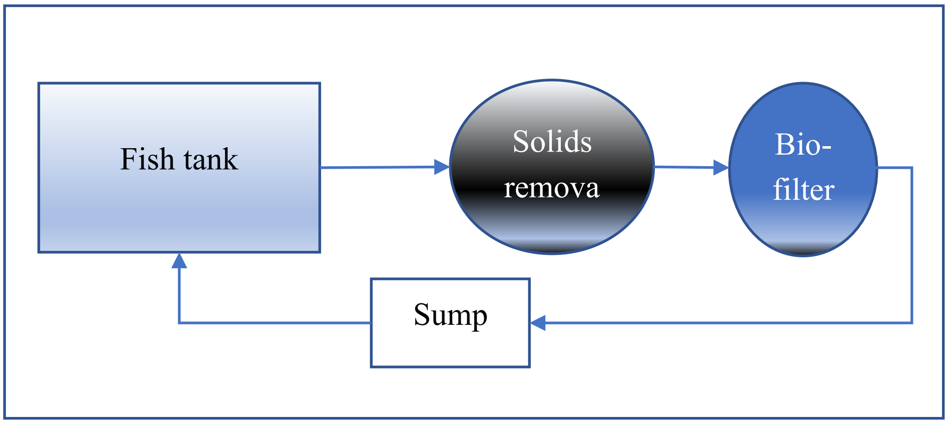

Figure 4. Conceptual set-up of recirculating aquaculture system (RAS).

The nitrification process consumes alkalinity, where the pH level in the system will decrease (Martins *et al.*, 2010; Martins *et al.*, 2009). The pH in the RAS will be maintained at around seven by adding bicarbonate into the system. Meanwhile, the solid wastes trapped in the solid waste removal must be discharged, and this is where the water exchange is needed in the RAS. The water exchange is also needed to reduce the nitrate concentration. Nitrate is the final product of nitrification and will accumulate in the RAS (Ramli *et al.*, 2017). The main challenges in RAS are maintaining higher efficiency in the solid removal and nitrification process and minimising the need for water exchange. As nitrate accumulates in the RAS, research is being conducted on how a denitrification unit can be installed and performed efficiently in a RAS and how the solid trapped in the RAS can fuel the denitrification process where nitrate concentration in the RAS can be decreased, thus eliminating the purpose of water exchange (Fontenot *et al.*, 2007; Ramli *et al*, 2008; Yogev *et al.*, 2017). Therefore, in the case of RAS, three parameters are identified as essential to be monitored and controlled (Table 2) (Ebeling *et al.*, 2006; Martins *et al.*, 2010; Mota *et al.*, 2015): dissolved oxygen of at least 5 mg L^{-1} to support fish and nitrification process, turbidity of water at the level below 1000 mg L^{-1} which could indirectly indicate C/N ratio (Ramli *et al.*, 2008), and pH level at 7. Probes are available commercially for the DO and turbidity levels. For C/N level, the value of C and N must be determined separately using laboratory analysis such as total organic carbon analysis and organic and inorganic nitrogen analyses.

2.3 Aquaponic System

The ability to have both fish or shrimp and vegetables makes aquaponic systems attractive to many farmers. The aquaponic system applies the basic principle of indoor RAS (Figure 5) and hydroponic principles (Love *et al.*, 2015). In aquaponic systems, fish wastes are used by the vegetables to grow, resulting in water purification. The components applied in the aquaponic system can be similar to those in RAS, as does the water quality requirement (Table 2). However, some units, such as the solids remover nitrification units, may be omitted, depending on the user's needs. For example, a nitrification unit may not be needed as the vegetables could use ammonia produced in the system and thus replace the function of nitrifying bacteria.

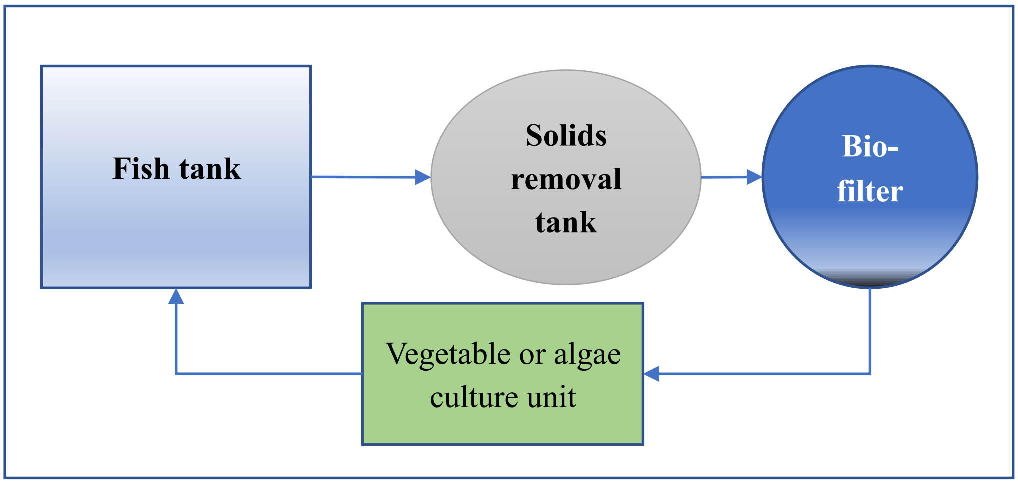

Figure 5. Conceptual set-up of an aquaponic system or RAS integrated with algae (Ramli *et al.*, 2018). An aquaponic system's fundamental design is similar to the recirculating aquaculture system. A vegetable or algae culture unit is integrated into the RAS set-up, which acts as a bio-filter to absorb ammonia, nitrate, and phosphate in the system.

Plants or vegetables that can grow under hydroponic culture systems are typically selected to be grown in aquaponic systems (Hu *et al.*, 2015). Continuous studies, either by formal research or by trial and error by farmers, are conducted to find the optimum yield for different types of fish and vegetables while maintaining a high water purification rate in aquaponic systems (Buzby & Lin, 2014; Neori *et al.*, 2017). Nitrogen removal rate by plants is species dependent as demonstrated by one study, nasturtium (a herbaceous flowering plant) was found to be better than lettuce in removing ammonia and nitrate from an aquaponic system (Buzby & Lin, 2014). The ratio of fish to vegetables influences the exchange rate of nutrients between fish and vegetables (Buzby & Lin, 2014). Too high nutrient concentrations originating from fish wastes may cause toxicity, or too few nutrients may cause poor vegetable growth (Rakocy *et al.*, 2006). According to Rakocy *et al.* (2006), the ratio of fish tank to vegetable growth unit depends on the type of fish and vegetables cultured and the type of hydroponic media used for growing the vegetables. For example, for an aquaponic system having tilapia and using pea gravels as hydroponic media, the recommended volume ratio for the fish tank and media is 1:2.

However, the nutrient composition of fish wastes might not serve as complete nutrients for the vegetables. For example, a study reported that nitrogen concentration was three factors lower, phosphorus concentration was ten factors lower and potassium concentration was 45 times lower than commercial hydroponic fertilizer, resulting in low-quality tomatoes (Graber & Junge, 2009). Nonetheless, the same study suggested that potassium hydroxide (KOH) could be added to aquaponic systems, which could serve two functions: to increase the pH level at which the nitrification process has decreased and to supply potassium as nutrients for the vegetables.

An article published in 2014 reported that aquaponic systems are more popular among hobbyists who actively explore and try new technologies in the United States and internationally (Love *et al.*, 2014). According to the same report, practising aquaponic farming is increasing, although the commercial level and contribution to the country's production are still in their infancy. However, the vegetables produced in the aquaponic environment are considered by many as organic vegetables (since fertilizer and pesticide cannot be introduced to safeguard the fish cultured), and therefore, might be sold at a higher price as compared to vegetables cultured at standard farming methods.

2.4 Green Water Technology

Being labelled as the green gold of the future, microalgae (phytoplankton) consist of a significant part of green water plankton, besides bacteria, protozoa, and zooplankton, which contribute at large to the production of many major freshwater aquaculture species (Neori, 2011). Green water has been the leading natural feed for the world's major planktivore species, such as Nile tilapia, rohu carp, bighead carp, catla and shrimp at hatchery and grow-out systems. The additional benefits of green water are for maintaining low nitrogen and phosphate because microalgae uptake these nutrients for their growth. Also, microalgae use carbon dioxide and produce oxygen, which helps reduce chemical oxygen demand (COD) in the water body. Microalgae contain high protein (from 40 to 70%), carbohydrates (from 10 to 65%) and lipids (from 5 to 45%) per microalgae dry weight and another significant range of polyunsaturated fatty acids (PUFA) such as docosahexaenoic acid (DHA, 22:6n-3), eicosapentaenoic acid (EPA, 20:5 n-3) and arachidonic acid (AA) which make them suitable for fish feed (Becker, 2013; Blasio & Balzano, 2021; Roy & Pal, 2015). Green water culture relies on a photoautotrophic process that depends on light for photosynthesis. Therefore, a wide diurnal variation of DO, pH and ammonia are usually observed in the system, which may cause difficulty in managing a stable environment in green water culture (Ebeling *et al.*, 2006). An aerator should mix the pond to assist in regulating gases and nutrient exchange and allow all the microalgal cells to receive light for photosynthesis. When the green water system is practised in a pond culture system, it is also called a high-rate algal pond (HRAP) system. This technology is one of the earliest described for improving aquaculture production systems. The high-rate algal pond is an intensive waste-water treatment pond that combines wastewater treatment, reclamation and algal biomass production (Benemann *et al.*, 1977; Leong *et al.*, 2021)). The pond is shallow and continuously aerated normally by a paddle wheel to allow a homogenous chemical environment and to avoid pond stratification (Brune *et al.*, 2003). Inorganic nitrogen, phosphate and metal accumulation reductions in fish were observed in marine recirculating systems treated with HRAP (Li *et al.*, 2019; Metaxa *et al.*, 2006; Pagand *et al.*, 2000). As mentioned, microalgal cells in green water cultures assimilate ammonia, thus lowering ammonia levels in ponds. When carnivorous species are cultured, and these fish do not consume the microalgae, the biomass of microalgae could increase. The biomass should be controlled because the high density of microalgal cells will limit light penetration into the pond, thus limiting photosynthesis. Later, dead microalgal cells will cause decomposition and change the green water culture into a heterotrophic state, which may cause oxygen deficit in the system. Therefore, to control the microalgal population, some farmers will apply a co-culture of carnivorous and herbivorous fish (Chen *et al.*, 2010; Pagand *et al.*, 2000). The function of herbivorous fish is to take up the microalgae as feed. This will control the microalgal population and promote the growth of new microalgal cells.

3. Engineering Approach Towards Innovation, Challenges, and Way Forward

In the systems mentioned above, important engineering innovation can be made for the following designs: 1) pond or tank design for fish, solids removal, and bio-filtration processes, 2) equipment and techniques for system aeration or mixing, and 3) monitoring of water quality levels such as DO, temperature, pH, and ammonia (Figure 6). These aspects are mainly crucial in improving and monitoring the ammonia removal processes. Since the removal of the ammonia process involves different types of organisms, the design method should consider the biological needs of the organisms. This ensures that the performance of the filtration system, be it mechanical or biological, is optimized.

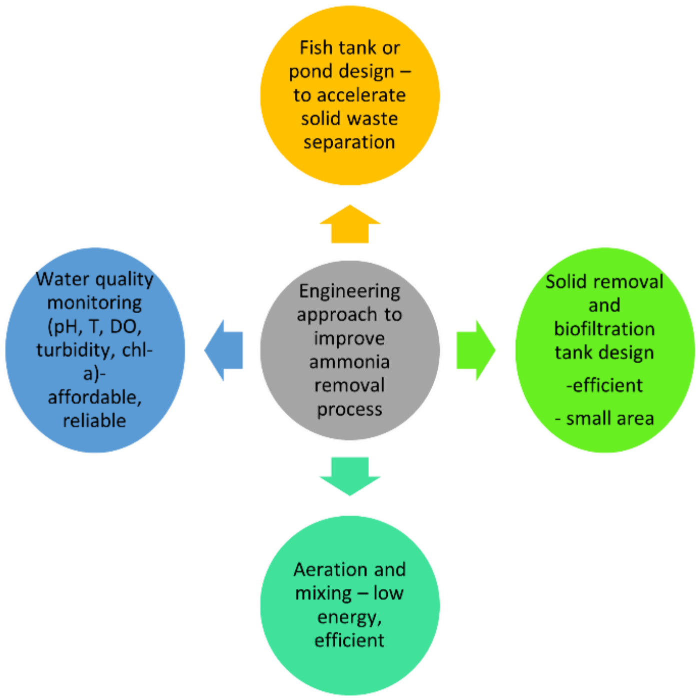

Figure 6. Components that can be improved using engineering approaches to enhance ammonia removal in aquaculture systems.

The innovation could increase water purification performance and consequently increase aquaculture production. For example, the nitrification process in an RAS requires maintaining a certain oxygen level; however, the farmers do not know the oxygen level until a DO sensor is attached to the tanks. If the DO is low, the farm operator should increase the DO level by increasing the aeration or injecting pure oxygen into the system. This issue is more severe in open pond systems where water quality is subjected to environmental changes.

Often, even though the farmers know that at a particular time, the DO level in the pond would become very low due to demand by fish and microbes and thus will start the paddle wheel to increase the DO level, this practice is done purely by assumption based on theoretical knowledge, or knowledge gained from years of experience. Even though the practice has been successful for the farmers, the proper use of technology, such as the Internet of Things (IoT), will be helpful to ensure that biological processes are at their optimum level. This also would increase energy farm use efficiency and minimize labour dependency (Prapti *et al.*, 2022; 2021).

Currently, other technologies, such as fish monitoring systems to observe growth, health, and behaviour, are developed and under constant improvement as these are another essential element to ensure good aquaculture practices which will contribute to high aquaculture production (Antonucci & Costa, 2020; Hung *et al.*, 2016; Zhou *et al.*, 2018).

Applying engineering knowledge in aquaculture comes with many challenges. The main challenge is understanding the complexity of cultured animals and their biota, which involve bacteria, fungi, plankton, and plants that inhabit an aquaculture environment and using suitable technology to support the aquaculture activity. For example, behaviour monitoring of fish or any crustacean species is not straightforward. An underwater high-quality camera must be used for behaviour monitoring. Often, the culture water is turbid and crowded, and the constant movement of the animal makes data collection and interpretation very difficult (O'Donncha *et al.*, 2021).

Another example is that data management and analysis are required for the IoT system to be applied with suitable sensors coupled with a sound internet communication system (Jebril *et al.*,2018; Antonucci & Costa, 2020; Gupta *et al.*, 2022). This technology is still expensive for farmers, especially in developing countries. Since aquaculture is considered a harsh environment subjected to climate fluctuations and high loads of nutrients, a robust IoT system is required, and technical experts are needed to maintain the system. Furthermore, aquaculture farmers are constantly challenged by risks of diseases, increases in production costs, mainly feed and energy costs, and labour shortages that could hinder technological advancement in their farms.

Finally, a significant challenge is determining stakeholders' roles in managing resources to enhance innovation. Acknowledging this fact, current research has highlighted the use of a modelling technique to assess the role of stakeholders in achieving an important objective. For example, a Triple Helix Model is developed to assess academia, industry, and government efficiency to boost innovation (Fidanoski *et al.*, 2022). This study used data from 30 developed countries to assess the overall innovation activities covering data from 2006 to 2018. The input variables are the education index (measure for academia in interaction with the government), industrial value added (measure for the industry in interaction with the government), and R&D expenditure (measure for government in interaction with academia).

Meanwhile, the output variable was patent applications which indicate the innovations. This study shows different scores of (in)efficiencies for different countries. For instance, the results show that all countries have low academic, industry, and government efficiency, except Greece, Luxembourg, Mexico, New Zealand, and Turkey. Research and development expenditure was found to be very inefficient and could be reduced while maintaining the same level of innovation. Reflecting on this study and our challenges in aquaculture innovation, we learn that data and thorough analysis are needed to conclude who should play more roles: government, academia, or industry. Although, in the Malaysian case, the ecosystem to support innovation is already in place, where farmers are making continuous efforts with support from academia and government, there is room for improvement. A similar study should be conducted considering relevant input variables so that efficient resource management and targeted contribution can be made. Adding more components, such as civil society and environment, to the analysis could give a more holistic perspective on innovation strategies that will contribute to innovation in technology and the management of society and the environment (Figure 7). Moving forward, policies such as the National Policy on Industry 4.0 and National Agrofood Policy 2021-2030 should serve as the backbone for innovation strategies while addressing the problems related to aquaculture.

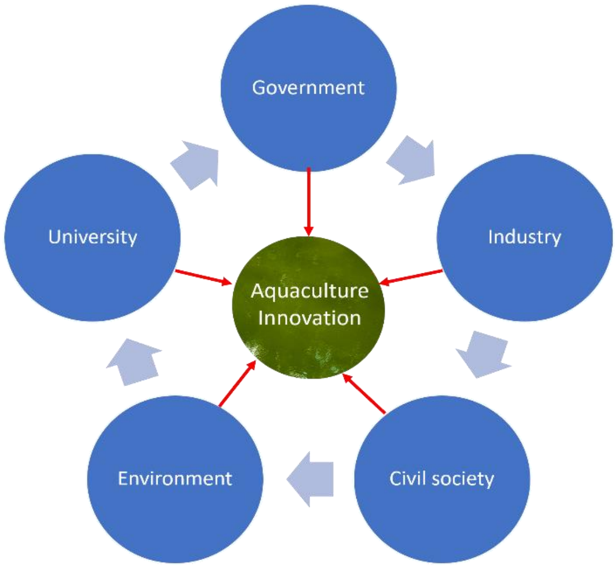

Figure 7. Quintuple helix aquaculture innovation framework (Adapted from Barcellos-Paula *et al.*, 2021).

4. Conclusions

Aquaculture production yields per hectare are heavily influenced by the type of aquaculture system utilized and its ability to maintain optimal water quality. Since ammonia is the most harmful nitrogenous waste in aquaculture systems, keeping its concentration below one mg/L is imperative. This review highlights three primary methods for ammonia removal: assimilation by algae or plants in green water technology and aquaponics, assimilation by heterotrophic bacteria in biofloc technology, and nitrification processes in RAS. Each method requires specific conditions, which can be indicated by monitoring key water quality parameters.

For bacterial processes, oxygen is crucial as bacteria require it for their metabolic activities. Additionally, pH monitoring is essential for all processes, as organisms thrive within specific pH ranges, and biological processes can influence pH levels. Depending on the specific process, parameters such as turbidity (for biofloc) should also be considered.

Understanding these key water quality parameters is vital for innovating and improving the ammonia removal process. Engineering approaches can play a crucial role, including pond or tank design improvements, solids removal, bio-filtration processes, and advancements in aeration or mixing systems. Moreover, continuous monitoring of water quality is essential for ensuring optimal conditions.

In conclusion, integrating relevant technologies to enhance the ammonia removal process holds great potential for increasing aquaculture production in Malaysia. This approach can effectively maximize the utilization of existing land resources, leading to increased production capacity in aquaculture in the years to come.

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