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Reduction in the environmental impact of waste discharged by fish farms through feed and feeding

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Abstract

The discharge of waste from aquaculture operations can lead to eutrophication and destruction of natural ecosystem in receiving water body. A controlled waste production strategy is necessary to maintain sustainable aquaculture growth into the future. As feed is the major source of waste in aquaculture, the management of aquaculture waste should be approached through diet formulation or feeding strategies. Highly digestible diets have been introduced as a solution to reduce solid waste excretion. Further reductions in solid waste can be achieved through careful selection of feed ingredients and feed processing to improve nutrient availability. An increase in faeces consistency by diet manipulation can improve solid removal efficiency. This condition can reduce the proportion of solids in discharged water in the effluent and also improve farm water quality. A reduction in dissolved nitrogen waste can be achieved by ensuring a balance between protein and energy causing fish to use non-protein sources as energy. Phosphorous waste can be decreased through careful ingredient selection and proper processing to improve digestibility. A proper feed ration and feeding method for each species should be adopted because feed waste constitutes a large part of waste production.

Key words: aquaculture, dissolved waste, environment, feeding method, solid waste.

Introduction

Aquaculture has developed quickly over the past few decades (FAO 2004). This fast growth is aimed at meeting two major purposes: food security and income generation. According to the FAO (2006), aquaculture continues to grow more rapidly than all other animal food-producing sectors. Since 1970, the growth rate of aquaculture has been 8.9% per year, which is much higher than other animal food-production sectors (2.8% per year; FAO 2006). This rapid growth has resulted in competition for natural resources (i.e. land and water; Piedrahita 2003). Apart from strong annual growth, the culture of fish over the past few decades has also been strongly intensified. This intensification has significant drawbacks, such as an increased environmental impact as a result of a larger amount of waste discharged by effluent water (Tacon & Forster 2003).

Aquaculture like other animal-production sectors generates waste. Aquatic animals cannot separate their living space from their area of excretion. This causes deterioration in water quality inside the production system, leading to poor growth and an increase in the incidence of disease (Losordo *et al.* 1999). Wastewater discharged from aquaculture is a major environmental concern because of possible environmental pollution to the receiving water, such as lakes or rivers (Pillay 1992; Cripps & Bergheim 2000; Amirkolaie 2008).

Management of the waste generated from fish is quite difficult and costly as the waste disintegrates and becomes diluted in the culture water. Wastewater generated from farms either has to be treated or discharged into the environment. Treatment of wastewater demands large investment and sophisticated equipment. The discharge of waste (both solid and dissolved) by effluent water from aquaculture operations can lead to eutrophication in the receiving water bodies (Persson 1991), which is often characterized by excessive growth of algae and/or aquatic plants.

There is a huge public consensus that waste produced in the aquaculture sector has to be reduced to minimize the negative impact on aquatic ecosystems. This has resulted in a strict standard for waste disposal into the environment in developed countries. According to these rules, the quality of wastewater has to be monitored to control the pollutant load, including the amount of phosphorus, organic matter and heavy metals (MacMillan *et al.* 2003).

Feed is the main source of waste and is also responsible for most of the environmental impact of aquaculture (Roque d'Orbcastel *et al.* 2009). The quantity and quality of the waste excreted by fish depend on intake, digestion and metabolism of dietary compounds (Bureau & Hua 2010). There is also a close connection between feed quality and feeding strategy and waste production (Cho 1992; Schneider *et al.* 2004a). Therefore, each strategy to reduce the impact of aquaculture waste has to focus on the composition of the feed and the feeding strategy. These strategies are based on two main approaches; improving the nutrient retention ability of the fish (Cho & Bureau 1997, 2001) and increasing waste removal efficiency (Brinker *et al.* 2005a; Amirkolaie *et al.* 2005a,b, 2006).

The present review investigates the influence of feed composition and feeding strategy on waste production and its characteristics. This information can contribute to the development of aqua-feeds that result in a reduction in waste discharge to the environment.

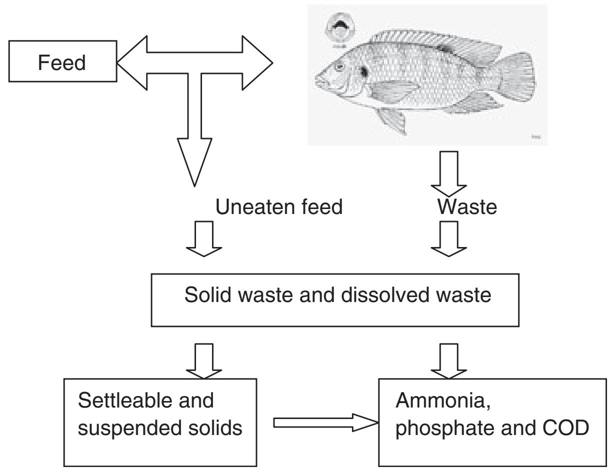

Figure 1 Scheme of waste production by fish (from Amirkolaie 2005).

Aquaculture waste

The waste produced by aquacultural operations can be divided into solid and dissolved waste (Fig. 1). The solid waste can be further split into settleable and suspended solids. Solid waste mainly originates from uneaten and/or spilled feed by the fish and from the faeces excreted. Part of the dissolved waste (i.e. chemical oxygen demand (COD), ammonia, phosphorous) originates from metabolites excreted by the fish (through the gills and in urine). Another part of the dissolved waste originates from the disintegration/suspension of nutrients from the solid waste fraction (both settleable and suspended).

In intensive aquaculture systems, between 20 and 40% of the dietary dry matter is incorporated into the fish body and the remaining part is excreted (Verdegem *et al.* 1999). The proportion of uneaten/spilled feed ranges between 5 and 15% (Beveridge *et al.* 1997; Cho & Bureau 1997). The amount of faecal waste depends on factors such as feed composition, fish species and temperature. The amount of faecal waste ranges between 0.2 and 0.5 kg dry matter per kg feed (Chen *et al.* 1997).

In all aquaculture systems, waste is partially discharged with the effluent water. However, the amount and composition of the waste discharged with the effluent water differs between the various types of aquaculture systems. For example, in flow-through systems all dissolved waste and suspended solids are released to the environment. In a recirculation system the waste discharge from the system is substantially reduced by a factor of 100 compared with classic flow-through systems (Blancheton 2000). In pond systems the total waste produced remains in the system and part of the organic waste matter is mineralized *in situ* (Verdegem *et al.* 2001).

Reduction in waste discharge to the environment

Feed quality improvement

Over the past few decades there have been many changes in feed technologies and feeding methods aimed at reducing the production of solid waste through uneaten/spilled feed (Enell 1995; Bergheim & Asgard 1996). Technological treatments such as extrusion and expansion have improved the physical characteristics of aqua-feeds (e.g. water stability, leaching characteristics) (Kearns 1993; Wilson 1994).

The digestibility of the ingredients and nutrient composition of the diets are the main factors affecting the total waste output in an aquaculture production system. Therefore, minimizing further the waste discharge from aquaculture should be managed through diet formulation and processing. Solid waste in aquaculture is mainly composed of undigested starch and fibre from grain and plant ingredients. Undigested protein and fat are low in solid waste as they are highly digestible by fish (Cho & Bureau 2001). Therefore, over the past few decades, research on the reduction of faeces output has concentrated on using highly digestible diets based on fishmeal and fish oil (Bureau & Cho 1999; Sugiura *et al.* 1999), excluding poorly digestible grain by-products (Cho & Bureau 2001). Today, comprehensive development of feed composition and feeding technology has improved the feed conversion ratio in rainbow trout to 0.9–1.2 versus 1.5–2.5 in the 1970s and early 1980s (Bureau & Hua 2010).

Solid waste removal efficiency

Application of highly digestible feed cannot solve completely the impact of faeces production because the scope of digestion in fish is limited and a fraction of the feed always remains undigested and is excreted as faeces (Cho *et al.* 1994). Furthermore, as a result of limited availability of fishmeal and fish oil in the future (Hardy 1996), the plant ingredient content of aqua-feeds in carnivorous fish will increase. Moreover, modern intensive systems for herbivorous and omnivorous fish will rely more on supplementary diets that contain high percentages of plant ingredients (Naylor *et al.* 2000). This change of technology will reduce the digestibility of aqua-feeds and thus increase again total faecal waste production (Table 1).

Removing the solid waste before it is discharged can be a solution for reducing the environmental impact of wastewater. Feed composition can alter the physical properties of faeces (Amirkolaie *et al.* 2005b), thereby influencing the efficiency of solid waste removal (Amirkolaie *et al.* 2005b). Stable faeces have a larger particle size and settle more quickly and are thus more efficiently removed by a settling basin. An increase in solid waste removal efficiency improves the proportion of settleable solids to non-settleable solids, thereby decreasing the production of organic matter and suspended solids within the system. Quick removal of solids also reduces mineralization of organic nitrogen (N) and phosphorous (P) by dissolved and particulate organic matter decomposition, thereby reducing the conversion of particulate N and P into dissolved N and P.

The proportion of dissolved waste is influenced by fermentation and the viscosity of digesta induced by undigested carbohydrate fractions in the distal intestine (Amirkolaie *et al.* 2005b, 2006). Soluble non-starch polysaccharides, such as guar gum, have been shown to increase digesta viscosity and reduce faeces removal efficiency in tilapia. However, insoluble non-starch polysaccharides such as cellulose did not change faeces removal (Amirkolaie *et al.* 2005b) because of lower fermentation activity.

Starch is a cheap source of energy and its inclusion in feed influences faeces stability (Han *et al.* 1996). Plant ingredients always contain a fraction of starch and the addition of starch to an aqua-diet can reduce the dissolved nitrogenous waste of many fish species by increasing the dietary non-protein energy content (Steffens *et al.* 1999; McGoogan & Gatlin 2000). Replacement of native starch with gelatinized starch improved the percentage of faeces removed, leading to lower dissolved faeces in the discharge water (Amirkolaie *et al.* 2006).

The addition of easily fermentable dietary ingredients leads to an increase in the proportion of small particles, thereby decreasing faeces removal efficiency (Amirkolaie *et al.* 2006). Viscose ingredients can also influence faeces characteristics. A slightly higher digesta viscosity induced by the addition of guar gum or alginate (Brinker *et al.* 2005a) or even a high starch level (40%; Amirkolaie *et al.* 2006) in the diet improves faeces stability by increasing elastic resistance in the digesta.

The addition of a small amount of binder to the diet is another approach that has been used to enhance faeces stability (Han *et al.* 1996; Brinker *et al.* 2005a,b). The inclusion of 0.3% of guar gum as a dietary binder increased the particle size of faeces and produced more compact particles than a binder-free diet (Brinker *et al.* 2005b). Guar gum addition also increased the buoyancy and suspension of particles induced by the large water absorbing capacity of the binder (Storebakken 1985; McMillan *et al.* 2003). This condition improves the efficiency of micro-screening techniques without having a negative impact on sedimentation (Brinker *et al.* 2005b).

Quick faeces removal from the system lessens the amount of solids undergoing bacterial decomposition, thus leading to improved water quality within the system and subsequently to a lower wastewater discharge

Table 1 Total faeces production and digestibility in tilapia fed on plant-based diets

Diet	Inclusion level (%)	ADC of dry matter (%)	Total faeces produced (g DM/kg feed)	References
Fishmeal	15	79.1	209	Amirkolaie (2005)
Soybean extract	15	80.2	198	Amirkolaie (2005)
Dried duckweed	15	77.6	224	Amirkolaie (2005)
Dried duckweed	40	71.1	283	Amirkolaie *et al.* (2005a)
Acha meal	30	60.5	395	Fagbenro *et al.* (2000)
Sorghum meal	30	63.9	361	Fagbenro *et al.* (2000)

Each experimental diet is composed of a basal diet plus a feed ingredient. ADC, apparent digestibility coefficient; DM, dry matter.

from the system, leading to less environmental pollution (Amirkolaie 2005).

Several solids separation technologies have been developed in intensive aquaculture treatment systems. Rotating micro-screens are often been installed at farms (Cripps & Bergheim 2000). The treatment efficiency of drum filters varies over a range of 67–97% for suspended solids, 21–86% for total P and 4–89% for total N (Twarowska *et al.* 1997).

Nitrogen waste

Ammonium is a by-product of protein catabolism. It has long been recognized that feeding excess protein will lead to catabolism of the amino acids associated with the excretion of ammonium and a loss of energy (Lloyd *et al.* 1978). Equilibrium between the amino acid quantity in feed and fish requirements can reduce the catabolism of amino acids.

In addition to the protein content of feed, a balance between the digestible protein and digestible energy of the diets can result in an increase in N retention efficiency and a decrease in the ammonium waste excreted by fish (Kaushik 1998; McGoogan & Gatlin 2000). Utilization of non-protein energy sources (fat or carbohydrate) to meet energy requirements can improve protein retention, thereby reducing ammonium waste into the water. This phenomenon is commonly called the 'protein sparing effect' and has been demonstrated in a number of species (Kaushik 1998).

As fish generally tend to burn protein as a main energy source, the scope of protein sparing in fish cannot solve completely the impact of ammonium production by fish. In an ideal ratio of dietary protein to dietary energy only 50% of the digestible protein can deposited in the body and the rest must meet the energy requirements of the fish (Cho & Bureau 2001).

Moreover, all fish species do not have a similar ability to use feed nutrients. These differences are related to physiological and/or anatomical differences between species (Table 2).

In salmonids, a protein energy ratio of approximately 18 g digestible protein per MJ digestible energy reduces amino acid catabolism without having a negative impact on growth or feed efficiency (Einen & Roem 1997). In a large number of other species, a diet containing 18–20 g digestible protein per MJ digestible energy appears to be effective in reducing considerably dissolved N waste.

Phosphorous waste

The digestibility of different chemical forms of P and the P content in feed are two important parameters affecting

Table 2 Average waste load on a dry matter, nitrogen and chemical oxygen demand (COD; g O_2) basis expressed as the percentage of feed intake for African catfish (*Clarias garriepinus*) and European eel (*Anguilla anguilla*) grown in recirculation systems on a diet containing 48–52% crude protein (Verdegem *et al.* 2001)

Type of loss	Dry matter (%)	Nitrogen (%)	COD (%)
African catfish			
Faecal losses	20	10	25
Non-faecal losses	50	55	40
Gain	30	35	35
European eel			
Faecal losses	30	15	15
Non-faecal losses	35	65	58
Gain	35	20	27

Table 3 Phosphorous balance of tilapia (*Oreochromis niloticus*) fed on six different experimental diets

Type of loss		Single cell			
	Duckweed	Protein	Fishmeal	Soy bean meal	Wheat gluten
Faecal losses	33	38	40	36	35
Non-faecal losses	40	42	37	48	39
Gain	27	20	23	16	26

Each ingredient is added into the basal diet at a 15% weight/weight ratio (data are from Schneider *et al.* 2004a).

the amount of P discharged into the environment. Digestibility of P varies between fish species and mostly depends on the stomach pH of the fish (Sugiura *et al.* 1999). For instance, in rainbow trout, a fish with a true stomach, bone P digestibility ranges between 40 and 60%; however, bone P digestibility is much lower for stomach-less fish such as carp (Lall 1991). Table 3 shows the indigestible fraction of P excreted in fish faeces. The P content of diets has dropped to below 1% to reduce the P load from fish farms (Enell 1995). Digested P is absorbed where it is deposited in the body of the fish (bones, scale, flesh). A fraction of digested P, however, is excreted in the form of dissolved waste via urine (Bureau & Cho 1999).

There is evidence suggesting that the efficiency of P deposition in fish decreases with an increase in P digestibility. Feed composition has a great impact on P digestibility, retention and loss (Amirkolaie 2005). Therefore, it is worth formulating a highly digestible diet containing a threshold P content.

An increase in the fishmeal content of aqua-feed for carnivorous species results in higher P excretion into the aquatic ecosystem as a result of the high P content of fishmeal. Plant protein ingredients, such as corn gluten and soybean meals, have a lower P in comparison to fishmeal or animal by-product meal; these characteristics are desirable for low pollution diet formulation (Cho *et al.* 1994). This condition minimizes dissolved P discharge and the potential contribution to eutrophication. However, diets containing significant amounts of plant ingredients will have more phytate (an organic compound). Phytate is not digestible to fish because they do not possess the enzyme (Phytase) that is required to release P from phytate (Cho & Bureau 2001).

All forms of P excreted by fish do not have an equal potential to pollute aquatic ecosystems. Dissolved P is highly accessible by plants and stimulates eutrophication. Undigested forms of P such as phytate should be mineralized by bacteria in aquatic environments (Persson 1991) and then utilized by plants.

Feeding strategy

Part of the feed given to fish is not consumed by the fish and is added to the solid waste budget. The feeding strategy deals with alternatives to reduce the uneaten feed and increase feed efficiency. Feed wastage and feed ration are highly correlated, leading to strong increases in waste production at higher feeding levels (Van der Meer *et al.* 1997). Therefore, *ad libitum* feeding is not advisable for waste production. The feeding level is adjusted according to a standard feed chart for each species (Cho & Bureau 1997) and should stop near satiation (under close-look). This condition can reduce feed costs, which constitute a major production cost in fish culture.

Several techniques have been used to deliver rations to fish and also to monitor feed intake in order to minimize feed losses (Cripps & Bergheim 2000). Hand feeding may be an efficient technique in terms of conversion of feed into waste as feed delivery stops when fish approach satiation. Different types of feeding systems have been developed including fixed feed ration systems and demand feeding systems. The choice of feeding system is based on fish size, feeding behaviour and cost. A demand feeding system may be suitable in an intensive large-scale fish farm to deliver high rates of feed with the least amount of waste. Uneaten feed monitoring technology is a useful means of reducing feed wastage (Summerfelt *et al.* 1995). An underwater video camera can monitor feed pellet level and count feed pellets in the sea cage to identify a feed-wastage event (Foster *et al.* 1995; Parsonage & Petrell 2003).

There is increasing evidence showing that feeding rhythms in fish are similar to other groups of animals (Madrid *et al.* 2001). This may cause variation in feed intake within a day or between days, months and/or years (Jobling & Baardvik 1991). These variations are related to environmental factors and/or the physiological status of the fish (Jobling & Baardvik 1991; Jobling 1994). The optimal time for feeding should be adjusted according to the natural daily feeding activity of the species (Bolliet *et al.* 2001). In salmonids, feeding activity is concentrated during the day (Helfman 1993). For example, feeding catfish during the day, a species that displays strong nocturnal behaviour (Boujard & Luquet 1996), may increase feed waste.

Feed frequency is also known to affect feed efficiency and feed wastage (Jarboe & Grant 1997). Feed efficacy increased when the number of meals was increased from two to four in channel catfish (Greenland & Gill 1979). Feed estimation will hardly match the feed requirement of the species because of a range of uncontrolled behavioural, physiological and environmental variables (Alanara *et al.* 2001). To minimize feed wastage, fish farmers must consider these conditions and estimate daily feed requirements according to these theoretical considerations.

Control of nutrient flow in intensive aquaculture systems

Integrating production system

Producing aquatic species in the same production system, referred to as polyculture, can decrease production costs, increase productivity and reduce waste discharge (Troell *et al.* 1999; Naylor *et al.* 2000). Polyculture of Chinese carps has been recognized as a traditional way of increasing nutrient utilization in ponds (Komen & Bovenhuis 2007). Seaweed and mussels can grow well in wastewater discharged from intensive fish farms, thereby reducing the nutrient and particulate loads to the environment (Phang *et al.* 1996; Soto & Mena 1999).

Recycling aquaculture waste

Alternatively the waste excreted by fish can be re-used inside the husbandry system and converted to harvestable products, such as vegetables (Graber & Junge 2009), meat (Soto & Mena 1999) or bacteria (Schneider 2006). Fish can retain 20–50% feed N and 15–56% feed P (Schneider *et al.* 2004b). The remaining N and P are released into the water and can be converted to valuable products by phototrophic and heterotrophic organisms (Schneider 2006). The bio-treatment of wastewater with algae to remove nutrients such as N and P has long been recognized as a solution to convert dissolved waste into harvestable products (Borowitzka & Borowitzka 1988; Komer & Vermaat 1998; Verdegem *et al.* 2003; El-Shafai 2004). Algae can be consumed by fish directly or can be used as an ingredient in fish feed (Schneider *et al.* 2004a; El-Shafai *et al.* 2004). The conversion of nutrients into harvestable products and the direct use of these products, such as plants and/or worms (Olive 1999; Luening *et al.* 2002), caused a significant increase in nutrient retention. However, using these products to feed other animals reduced overall nutrient retention (Schneider 2006).

Sludge produced from aquaculture solid waste is considered to be a good fertilizer with high contents of N and P for agricultural fields (Bergheim *et al.* 1993; Chen *et al.* 2002).

Conclusion

Numerous studies have examined nutritional strategies as a way of reducing waste production and minimizing the environmental impact of aquaculture waste. In recent years, feed quality and feeding method have been improved to meet this goal. This has resulted in a profound reduction in the waste output from many types of aquaculture systems. A second line of research has focused on improving the efficiency of faeces removal. Diet composition has a profound impact on the quantity and quality of waste in an aquaculture production system and subsequently a great impact on water quality inside the system and waste discharge into the surrounding water.

Waste output from aquaculture operations to the aquatic ecosystem may be reduced, but not completely eliminated because fish cannot retain all of the food they consume and part of the feed always remains uneaten. The waste output amounts to an equivalent of at least one-third of the feed input. However, pollution from fish farms can be significantly reduced by using highly digestible feed, more consistent faeces, a proper feeding strategy and a careful balance of energy and nutrients, particularly N and P, which affect eutrophication. The waste can also be managed outside the production system by converting it into re-useable products.

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