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A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture

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Abstract

Significant efforts should be devoted to reducing waste outputs from aquaculture operations in order to lower the environmental impacts of aquaculture in many parts of the world. Since most aquaculture wastes are ultimately from dietary origin, reduction of waste outputs should first be through improvements of diet formulation and feeding strategies. The first step in the production of feeds producing less solid waste is to eliminate poorly digestible ingredients (such as whole grain or grain by-products used as binders and fillers in the feed formulae) and to use highly digestible ingredients with good binding properties. Further reduction of solid waste can then be achieved through careful selection of the ingredients to improve apparent digestibility and the nutrient balance of the feed. Nitrogen waste outputs can be reduced through the reduction of the digestible protein to digestible energy (DP/DE) ratio of the diet. Phosphorus waste outputs can be reduced through careful selection of the ingredients and optimization of the digestible phosphorus content of the diet to meet the requirement of the fish but avoid greatly exceeding this required level. Finally, feeding practices that minimize feed wastage should be adopted since feed wastage can have a very significant impact on waste outputs from fish culture operations.

Keywords: aquaculture, waste, feed, feeding

Introduction

Overt the past decade, the environmental impacts of aquaculture operations have become a matter of concern for the public, the various levels of government and the aquaculture producers themselves. Minimizing environmental impacts is therefore a key factor in insuring long-term sustainability of the aquaculture industry.

Containment and collection of wastes, both solid and dissolved, is very difficult and costly in aquaculture, as the wastes are rapidly dispersed into the surrounding waters. The release of solid wastes, phosphorus (P) and nitrogen (N) from aquaculture operations may have significant eutrophication effects on receiving waterbodies and associated ecosystems (Persson 1991). P waste outputs are a greater concern in freshwater since P is generally the most limiting factor for plant (algae) in that environment. N waste outputs are generally a greater concern in the marine environment for the same reason (Persson 1991). Solid wastes (faecal material and wasted feed) settling to the sediment can have an impact on the benthic ecosystem of inland and marine waters (Gowen, Weston & Ervik 1991). Degradation of organic waste by bacteria and other organisms leads to the consumption of oxygen (O_2) through respiration. Excessive settling of organic matter may result in a significant reduction in dissolved oxygen (DO) levels and the creation of anoxic conditions that can be damaging to the benthic biota. The hypolimnion of freshwater lakes is most sensitive to this phenomenon since it has a poor capacity of regenerating its oxygen content (Gowen *et al.* 1991).

Since most aquaculture wastes are ultimately from dietary origin, efforts to reduce waste outputs should focus on nutrition and feeding, mainly through improvements of diet formulation and feeding strategies.

Estimating waste output

Prior to setting goals for reducing waste outputs one must have access to objective estimates of the amount of the different wastes produced. Directly monitoring and estimating quantitative waste outputs from effluent of aquaculture facilities is a costly process that can also be inaccurate (Cho, Hynes, Wood & Yoshida 1991). It is also nearly impossible for certain types of facilities, such as cage culture operations.

The biological method for the prediction of aquaculture waste outputs (BMPAWO) has been developed as a simple and economical alternative to limnological (chemical) methods of estimating waste outputs. BMPAWO uses a simple nutrient balance approach to estimate waste outputs (Cho *et al.* 1991; Cho, Hynes, Wood & Yoshida 1994). Ingested feedstuffs must be digested prior to utilization by the fish. The digested protein, lipid and carbohydrate are the potentially available energy and nutrients for maintenance, growth and reproduction of the animal. The remainder of the feed (undigested) is excreted in the faeces as solid waste (SW), and the by-products of metabolism (ammonia, urea, phosphate, carbon dioxide, etc.) are excreted as dissolved wastes (DW) mostly by the gills and kidneys. The total aquaculture wastes (TW) are made up of SW and DW, together with apparent feed waste (AFW). Since direct estimation of AFW is very difficult, best estimate can only be obtained by comparison with theoretical feed requirement, such as those estimated with bioenergetic models (Cho & Bureau 1997, 1998). This is discussed later in this review.

Using the BMPAWO approach, total solid waste (TSW) output is estimated by:

$$\text{TSW} = [\text{feed (DM basis) consumed} \times (1 - \text{ADC DM})] + \text{AFW (DM basis)}$$

Solid N (SNW) or P (SPW) waste output are estimated by:

$$\text{SNW or SPW} = [\text{N or P consumed} \times (1 - \text{ADC of N or P})] + (\text{N or P from AFW})$$

Dissolved N or P waste outputs (DNW or DPW) of the fish are estimated by:

$$\text{DNW or DPW} = (\text{N or P consumed} \times \text{ADC of N or P}) - (\text{N or P retained})$$

where DM is dry matter and ADC is the apparent digestibility coefficient.

This approach and a chemical procedure for quantifying waste outputs in the effluent have been compared by Cho *et al.* (1991). It was shown that continuous sampling (i.e. chemical or limnological method) of the effluent ($3\ \text{L h}^{-1}$, $24\ \text{h day}^{-1}$ for 12 weeks) did not yield satisfactory results, despite being very costly. Total solid and P determined using the chemical procedure were greatly overestimated (solid 59% and P 112% of intake) because of the difficulties involved in taking homogeneous water samples from 24 million litres of effluent during the 12-week period. However, the BMPAWO provided much more realistic values. N waste values by both methods were remarkably similar. The limnological method is likely to yield a more reliable waste estimate for N compared with solid and P wastes, because a high proportion of N is excreted as dissolved, and is therefore homogeneously mixed in the effluent. The study of Cho *et al.* (1991) and a follow up one by the same authors (1994) indicated that the principle of BMPAWO was valid. The BMPAWO is more flexible since it can be adapted to a variety of conditions and rearing environments. It can also be used *a priori* or *posteriori*, i.e. long before or after fish are in the water. This is especially useful when planning production or auditing aquaculture operations. The BMPAWO is also more practical and often more accurate than directly measuring waste outputs of fish (e.g. ammonia, phosphate) through sampling of water from aquatic systems when conducting nutrition research.

Reduction of waste through diet formulation

Digestibility of the ingredients and nutrient composition of the diet are the main factors that affect waste outputs by fish. Minimizing waste outputs from aquaculture operations should therefore start at the source, the diet formula.

Reducing solid waste

SW outputs by fish fed practical diets consist largely of undigested starch and fibre (cellulose, hemicellulose, oligosaccharides, pectins, lignin, polyphenols, etc.) from grain and various plant products, and minerals from the various ingredients. Undigested protein (N) and lipids are usually low since protein and lipid ingredients used in fish feeds are, in general, highly digestible. The amount of information on ADC of dry matter, protein, lipid, carbohydrate and minerals of common fish feed ingredients is ever expanding. However, estimates of ADC of protein of certain ingredients (e.g. fish meal, soybean meal, feather meal, poultry by-product meal) are highly variable in the literature. This variability is probably the result of:

(1)the difference in faecal material collection method used (stripping, dissection, St-Pée system, TUF column, Guelph system or passive collector);

(2)experimental errors (suboptimal experimental conditions, leaching, analytical errors, erroneous calculations, etc.);

(3)differences in the manufacturing and chemical composition of the ingredients (raw materials, processing technique, heat damage, etc.); and

(4)biological and environmental differences (fish species, fish size, water temperature).

It may sometimes be difficult to determine which published values are most realistic or reliable for the actual ingredients that will be used in the formulation. However, a number of sources (Cho & Kaushik 1990; Lall 1991; NRC 1993; Cho & Bureau 1997; Guillaume, Kaushik, Bergot & Métailler 1999; Sugiura & Hardy 2000) have summarized information on ADC of dry matter, protein, lipid, P and energy of common feed ingredients and this information has proven reliable and helpful.

Reduction of SW outputs from aquaculture operations can be fairly simply done by using highly digestible ingredients with high protein and/or lipid contents and excluding poorly digested, low-energy and low-protein ingredients, such as grain by-products rich in starch and fibre, to increase the digestible nutrients and energy density of the feed. This has long been recognized in other fields of animal nutrition (e.g. Scott, Nesheim & Young 1976). A basic example could be if 20% undigestible material was removed from a feed formula. Recalculation of the diet without this indigestible material would give a diet with 100/80 times higher energy (21 vs. 17 MJ DE kg^{-1}) and higher protein (47.5% vs. 38%), while the digestible protein to digestible energy (DP/DE) ratio (or the balance between digestible nutrients) would remain constant (DP/DE = 22.5 g MJ^{-1}). This type of diet can be termed a high nutrient density (HND) diet.

A practical example of a regular grower diet and an HND diet derived from the same basic ingredient matrix is presented in Table 1. A study conducted at a governmental fish culture station showed that using the HND diet (MNR-91H) resulted in an output of less than 190 kg total solid waste and 3 kg P per tonne of fish produced compared with 240 kg and 4 kg respectively with the regular grower diet (MNR-89G) (Cho *et al.* 1994). The cost of the MNR-91H feed was higher per unit of feed weight but feed cost per unit of fish produced was similar since feed efficiency (gain:feed) was improved (Cho *et al.* 1994).

The first step in the production of feeds producing less SW is therefore to eliminate poorly digestible whole grain or grain by-products used as binders and fillers in the feed formulae, and to use highly digestible ingredients with good binding properties. Further reduction of SW can then be achieved through careful selection of ingredients, notably the protein sources. An example could be the substitution of soybean meal (ADC dry matter = 74%) by corn gluten meal (ADC dry matter = 80%) (Cho & Bureau 1997).

Reducing dissolved nitrogenous wastes

The main factors affecting dissolved nitrogenous waste (DNW) outputs are those that influence the catabolism and deposition (retention) of amino acids (protein) by the fish. Amino acid composition of the diet is a factor with a determinant effect on DNW. It is well known that feeding amino acids in excess of requirement will result in the catabolism of the amino acid with associated excretion of ammonia and loss of energy (Lloyd, McDonald & Crampton 1978). Another key factor is the balance between digestible protein and digestible energy of the diet (DP/DE ratio) (Kaushik 1994). Numerous studies have shown that decreasing the dietary DP/DE ratio, by increasing dietary nonprotein energy content, results in an increase in N retention efficiency and a decrease in DNW of numerous fish species (Lee & Putnam 1973; Cho, Bayley & Slinger 1976; Watanabe 1977; Takeuchi *et al.* 1978; Watanabe, Takeushi & Ogino 1979; Kaushik & Oliva-Teles 1985; Cho & Woodward

Table 1 Practical grower (MNR-89G) and HND (MNR-91H) diet formulae for salmonids

Ingredient (%)	MNR-89G	MNR-91H
Fish meal (68%CP, 10% fat)	20.0	35.0
Blood meal (80% CP)	9.0	9.0
Corn gluten meal (60%CP)	17.0	15.0
Soybean meal (48% CP)	12.0	14.0
Wheat middlings (17% CP)	20.0	0
Whey (12% CP)	8.0	10.0
Vitamin premix (VIT-8905)	0.5	0.5
Mineral premix (MIN-8404)	0.5	0.5
Fish oil, marine	13.0	16 .0
Total	100.0	100.0
Nutritional specifications		
Digestible energy (DE) min. (MJ kg^{-1})	17	20
Digestible protein (DP) (g MJ DE^{-1})	22	22
Digestible fat (DF) (%)	16	20
Total phosphorous (%)	0.9	0.8
Expected feed efficiency, better than	1.0	1.2
Biologically estimated wastes (kg t fish produced^{-1})		
Total solids, max.	240	190
Nitrogen solid	10	6
Nitrogen soluble	40	33
Phosphorous solid	4	3
Phosphrous soluble	2	1.5
Fines (%)	1.5	1

Source: Cho *et al.* (1991).

1989; Johnsen & Wandsvik 1991; Einen & Roem 1997; Arzel, Métailler, Le Gall & Guillaume 1998; Helland & Grisdale-Helland 1998b; Hillestad, Johnsen, Austreng & Asgard 1998; McGoogan & Gatlin 1999; Santinha, Médale, Corraze & Gomes 1999; Steffens, Rennert, Wirth & Krüger 1999; McGoogan & Gatlin 2000). The improvement in N retention and the decrease in N excretion is due to the utilization of nonprotein energy sources for meeting energy requirements, resulting in a reduction of catabolism of amino acid (Lloyd *et al.* 1978), in what is commonly referred to 'protein sparing' (Kaushik & Cowey 1991). Protein sparing by dietary lipids has been shown to occur in most fish species (Kaushik 1998). Protein sparing by digestible carbohydrate such as gelatinized starch has also been demonstrated (Kaushik & Oliva-Teles 1985), but may be limited especially when the diet already contains a high level of lipids or has a relatively low DP/DE ratio (Lanari, D'Agaro & Ballestrazzi 1995; Bureau, Kirkland & Cho 1998; Helland & Grisdale-Helland 1998a).

Overall, experimental data suggest that a DP/DE ratio of about 18 g MJ^{-1} effectively reduces amino acid catabolism (and consequently DNW) without affecting growth rate and feed efficiency of salmonid fish species. Higher DP/DE ratios are generally required by smaller salmonids compared with larger ones to maximise growth (Cho & Kaushik 1990; Einen & Roem 1997). The formulation of diets that are high in protein and fat with 18–20 g digestible protein per MJ digestible energy and a digestible energy level equal or exceeding 20 MJ, have been shown to be effective for the management of DNW for a large number of fish species.

Total digestible N retention efficiency rarely exceeds 50% in rainbow trout (60% in Atlantic salmon) fed a diet with a low DP/DE ratio (16–18 g DP (MJ DE)$^{-1}$). It is not clear to what extent this significant catabolism of amino acids, despite an ample supply of nonprotein energy (shown by very high lipid deposition), is related to inevitable losses (maintenance requirement, inevitable catabolism) of amino acids or catabolism of amino acids that are in excess of requirement. Most studies on amino acid requirement have focused on the minimum dietary concentration of individual amino acids required to maximize performance. Few studies have attempted to integrate available information. The impact of the energy content of the diet and the overall amino acid composition (or amino acid balance) of the diet on the utilization of amino acids, and consequently DNW, is still a controversial topic (Cowey & Cho 1993; Rodehutscord, Borchert, Gregus, Pack, & Pfeffer 2000a; Encarnacao & Bureau 2001). More work on this is required.

Reducing P waste

The P content of common fish feed ingredients is highly variable. Some practical ingredients contain limited amounts of P (e.g. 0.3% P in blood meal), whereas others contain very significant levels (4%–5% P in meat and bone meal). P is present in different chemical forms in feed ingredients. Digestibility of the different chemical forms of P is known to vary widely (Lall 1991). P contained in organic compounds, such as phospholipids and nucleic acids, are apparently highly digestible to fish. P contained in phytate (inositol hexaphosphate), also an organic compound, however, is not digestible to fish since they lack the enzyme necessary to release P (phytase). The digestibility of mineral forms of P, such as dicalcium phosphate, monosodium phosphate and rock phosphate, varies with the degree of solubility of the compound(s) and is, consequently, highly variable (Lall 1991). The digestibility of P contained in bone (apatite) is variable between fish species and depends mostly on stomach pH of the animal (Lall 1991; Sugiura, Raboy, Young, Dong & Hardy 1999). For rainbow trout, a fish with a true (acid) stomach, the ADC of bone P appears to be between 40% and 60%. ADC of bone P appears to be much lower for stomachless fish, such as carp (Ogino, Takeushi, Takeda & Watanabe 1979; Lall 1991). Ogino *et al.* (1979) reported that the ADC of P of white fish meal was 10%–26% for common carp, whereas it was 60%–72% for rainbow trout. Other factors, such as particle size, feed processing technique and enzyme treatment, are also known to affect the ADC of P (Lall 1991; Vielma, Ruohonen & Lall 1999).

A negative effect of dietary P level on the ADC of P has been suggested by some authors (Vielma & Lall 1998; Sugiura *et al.* 1999; Avila, Tu, Basantes & Ferraris 2000; Rodehutscord, Gregus, & Pfeffer 2000b). However, the limited range of data available and the relatively large experimental error often associated with micronutrient digestibility measurements with fish, do not allow a definite conclusion to be reached at this point in time. The definition of the effect of dietary level and deficiency, as well as the chemical form of dietary P on the ADC of this element, is an interesting and rather complex problem. A more definite answer may be only achievable with elaborate experimental designs, notably dietary design, and sophisticated techniques allowing accurate determination of P digestibility and of the origin of the P digested (endogenous vs. dietary origin, organic vs. inorganic, etc.).

At this point in time, it appears that the ADC for P of common feed ingredients of Lall (1991) and those of Satoh, Tanezawa & Watanabe (1998) are fairly reliable and additive (Bureau & Cho 1999). These ADC, as well as those recently published by Sugiura & Hardy (2000), offer an adequate starting point for the formulation of diet-minimizing DWP waste outputs.

Numerous studies have shown that dietary incorporation of microbial phytase improved the ADC of P of fish fed diets containing phytic acid (Rodehutscord & Pfeffer 1995; Schaefer, Koppe, Meyer-Burgdorff & Guenther 1995; Riche & Brown 1996; Scott Jackson, Li & Robinson 1996; Eya & Lovell 1997; Li & Robinson 1997; Hughes & Soares 1998; Lanari, d'Agaro & Turri 1998; Oliva-Teles, Pereira, Gouveia & Gomes 1998; Vielma, Lall, Koskela, Schöner & Mattila 1998; Forster, Higgs, Donsanjh, Rowshandeli & Parr 1999; Papatryphon, Howell, & Soares 1999; Papatryphon & Soares 2001; Vandenberg 2001). The use of phytase is appropriate only for diets with digestible P contents below the requirement of the fish and containing significant levels of plant ingredients, i.e. in which a significant proportion of the P is as phytate-P. There are a number of other factors to consider. The activity of this enzyme is affected by environmental temperature and its activity may be limited at low water temperatures, i.e. 5–10°C (Forster *et al.* 1999; Vandenberg 2001). Moreover, the enzyme is sensitive to heat and may be destroyed during pelleting and extrusion under standard commercial conditions. This problem may be rather easily circumvented through postpelleting applications and possibly encapsulation of the enzyme (Papatryphon & Soares 2001; Vandenberg 2001). Pretreatment of plant ingredients with phytase prior to their incorporation in fish feeds has also been suggested and shown to be highly effective (Cain & Garling 1995; Storebakken, Shearer & Roem 1998; Mwachireya, Beames, Higgs & Dosanjh 1999; Ramseyer, Garling & Link 1999; van Weerd, Khalaf, Aartsen & Tijssen 1999). However, ingredient pretreatment is often impractical and may result in additional cost. Low phytate varieties of grains and oilseeds are increasingly available and their use could be helpful to minimize undigestible phytate P in feeds and, consequently, faecal P output (Sugiura *et al.* 1999).

Both digestibility and quantity will determine the fate of P fed to fish. The undigested fraction of the P of the diet is excreted in the faeces by fish. The fraction of P digested by the animal is absorbed where it is deposited in the body of the fish (bones, scales, flesh, etc.) in the growth processes. A large body of experimental evidence suggests that there is a requirement to maximize growth and P deposition and bone mineralization. The P requirement of rainbow trout for maximum growth is 0.37% digestible P (0.19 g MJ DE^{-1}) and 0.53% (0.27 g MJ DE^{-1}) for maximum P deposition (Rodehutscord 1996). There is still a question about the necessity of maximizing mineralization of the skeleton of fish for long-term maintenance of health and performance (Rodehutscord 1996; Asgard & Shearer 1997; Vielma, Makinen, Ekholm & Koskela 2000).

Fish receiving only the amount of digestible P needed to meet requirements for growth excrete only minute amounts of nonfaecal P (*c.* 5 mg *P* kg^{-1} BW d^{-1}), indicating that the digestible P intake of the fish is directed almost completely toward deposition (Rodehutscord 1996; Vielma & Lall 1998; Bureau & Cho 1999; Sugiura, Dong & Hardy 2000a; Sugiura, Dong & Hardy 2000b). There is evidence that efficiency of P utilization tends to decrease as the digestible P level increases from the level required for maximum growth to the level required for maximum P deposition (Rodehutscord 1996; Rodehutscord *et al.* 2000b). Interpretation of available data suggest that, while feeding a diet with digestible P at the level required to maximize growth results in minimal nonfaecal P excretion, feeding a diet with a digestible P level required for maximum P tissue deposition results in significant nonfecal P excretion (Rodehutscord 1996; Bureau & Cho 1999; Sugiura *et al.* 2000a, b).

DPW are excreted mostly as phosphate via the urine (Kaune & Hentschel 1987; Renfro 1997; Vielma & Lall 1998; Bureau & Cho 1999). In mammals, urinary phosphate excretion is determined mostly by plasma phosphate concentration (Bijvoet 1980). A threshold plasma phosphate concentration exists below which phosphate excretion is minimal and above which phosphate excretion is proportional to the increase in plasma phosphate. Because teleost fish and mammals share similar renal physiology (Dantzler 1989), a similar threshold relationship between plasma phosphate and urinary phosphate excretion should also exist in teleost. This was recently confirmed by Bureau & Cho (1999), who estimated this threshold at a plasma inorganic P concentration of 86 mg l^{-1} for rainbow trout weighing about 200 g. Data from Vielma & Lall (1998), Rodehutscord *et al.* (2000b), and Sugiura *et al.* 2000a, b) also support the existence of a threshold for urinary excretion of P. It might be reasonable to conclude that a digestible P level producing a plasma phosphate concentration near the renal P excretion threshold concentration should be acceptable from a biological (the fish) point of view and optimal from a waste management point of view. Experimental evidence suggests that this level is around 0.4% digestible P (0.2 g MJ DE^{-1}) for rainbow trout (Rodehutscord *et al.* 2000b). At that level, growth of rainbow trout is maximized, ‘acceptable’ (not maximal) P deposition is achieved (i.e. the acceptable level from the point of view of the fish since at this level the plasma phosphate pool saturates renal reabsorption systems) and DPW output is minimal. Similar views were expressed by Sugiura *et al.* 2000a, b.

We believe that the amount of information available on the ADC of P of common feed ingredients and the P utilization and requirement of fish can now allow the formulation of diets resulting in less P waste output for salmonids and, arguably, most fish species.

It might be worth noting that not all forms of P excreted by fish have an equal potential to contribute to eutrophication. In order to be utilized by algae and other plants, P must be soluble. DWP is therefore highly available to plants and may greatly stimulate eutrophication. In nature, solubilization of SWP can be the result of either a simple chemical equilibrium or the action of enzymes or chemicals (acids) by bacteria and other organisms. To what extent SWP will be mineralized and solubilized in the environment will be dependent on both the chemical make-up of SWP and the prevailing conditions. Organic forms of P that are not digested by the fish (e.g. phytin-P) will be excreted as SWP but can be mineralized by bacteria and other organisms in the aquatic environment (Persson 1991). Calcium-bound P, as is found in bones (apatite-P), is in most cases inert under normal environmental conditions (Persson 1991) and may have no or little potential to stimulate eutrophication.

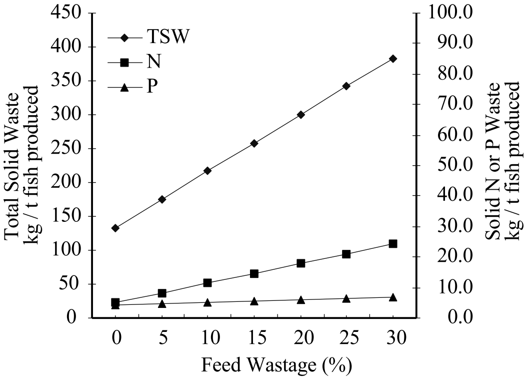

Figure 1 Effects of feed wastage on total solid, solid N and solid P waste outputs of rainbow trout fed a practical diet and growing from 10 to 100 g live weight at 15°C.

Reducing waste outputs through feeding strategies

Feed cost is a major production cost in fish culture yet feeding fish is still mostly guesswork, each fish producer adopting different practices or following different guidelines (feed charts). Feeding too much leads to feed wastage, a pure economic loss, and greater waste output. Conversely, feeding too little results in less growth and this can also represent an economic loss. Feeding strategies minimizing feed and total production costs as well as waste outputs per tonne of fish produced are key to the economic success and sustainability of fish production.

Many producers rely on feeding charts provided by feed manufacturers or found in various publications. One must be cautious in applying these charts. The wide range of fish species, genetic stocks, feed composition, water temperature and growth rates encountered on fish farms makes it impossible to develop a single feed chart that would be correct for all individual farm situations. Indiscriminate use of these charts or careless feeding practices (e.g. poorly adjusted and monitored demand feeders) may result in significant feed wastage, waste outputs and economic losses. Under all farm situations, some feed wastage is likely always occurring. The scientific estimation of feed allowance and careful monitoring of feed allowance and utilization of the fish may be the best possible approaches to minimizing feed wastage.

Figure 1 illustrates the importance of minimizing feed waste from a waste output point of view. Only a small proportion (*c*. 15%–25%) of a given amount of feed consumed by a fish will be excreted as SW. Feed that is not consumed by the animal, on the other hand, will become 100% solid and suspended wastes. Figure 1 shows that as feed wastage increases from 0% to 30% (in this example when an FCR (feed/gain) of 1.11 is obtained instead of 0.83), what was biologically achievable, solid N waste (SNW) outputs by the fish quadruples, SW triples and SPW is increased by about 60%.

Feed wastage depends mostly on the feeding practices used rather than on the feed itself. Since direct estimation of AFW is very difficult, best estimate can be obtained by comparison with theoretical feed requirement calculated with an approach in which the expected feed or energy efficiency indicates the degree of AFW for a given operation (Cho & Bureau 1998).

The feed requirement is generally governed by how much energy, protein, fat and minerals the animal deposits in its body and the biological cost of depositing these body components. Fish retain in their body a large proportion of the nutrients/energy fed to them. Their feed and energy requirements are therefore very closely related to the rate of body component accretion. Sufficient data on growth process and nutritional energetics are now available to allow reasonably accurate feeding standards to be computed for salmonid fish species as well as a number of marine fish species (Kaushik 1998; Lupatsch & Kissil 1998; Lupatsch, Kissil, Sklan, & Pfeffer 1998). A series of bioenergetic models were developed by Cho (1992) and improved by Cho & Bureau (1998) and Bureau, Azevedo, Tapia-Salazar & Cuzon (2000). This series of models predicts growth and energy requirements to determine feeding standards and expected feed efficiency for salmonids. Calculation of the feed requirement using this rational approach involves five steps:

(1) Diet selection

The amount of feed required by fish depends first on the composition of the feed. In general, a greater amount of a lower nutrient density feed will be required than a higher nutrient density feed to achieve the same performance level (Table 1), if two feeds have similar protein and energy balance. Composition of the feed can also affect the composition of the fish produced (i.e. the amount of protein, lipid, mineral deposited) and this, in turn, can possibly affect the amount of feed required.

(2) Growth prediction

The accurate prediction of the growth of fish over the period for which the feed requirement is calculated is probably the most critical factor for the accurate prediction of feed requirements. Growth involves the deposition of nutrients (accretion of body components), which is the main factor determining feed requirement. Fish growing at different rates will therefore have different feed requirements. Production records are very valuable starting points when trying to predict the growth of the fish for which one wants to calculate ration allowance. A growth model, the thermal-unit growth coefficient (TGC), has been developed to help predict the growth of fish based on previous production records and the current water temperature profile (Cho 1992). It is important to note that the instantaneous growth rate model, better known as the specific growth rate (SGR) model, is not reliable and its use should be avoided since it would result in serious bias in feed requirement estimation (Cho 1992; Cho & Bureau 1998; Bureau *et al*. 2000).

Live weight gain is the result of deposition of water, protein, fat and minerals. The amount of these components deposited per unit of live weight gain is not constant but rather changes with fish species and size, feed used, etc. For this reason, knowledge of the composition of the fish reared is another key factor for the accurate determination of feed requirement. Patterns of nutrient deposition have received little attention in the past. A limited number of studies on the topic appear to indicate that growth and nutrient deposition follow rational patterns (Shearer 1994; Azevedo, Cho, Leeson & Bureau 1998; Lupatsch *et al.* 1998; Bureau *et al.* 2000). Growth of salmonids over a wide range of body sizes has been shown to be accurately described by the TGC model (Cho 1992). Studies with rainbow trout reared at different water temperatures (Azevedo *et al.* 1998; Rodehutscord & Pfeffer 1999) have shown that protein and lipid deposition increased linearly with increasing metabolizable energy intake, regardless of body weight or water temperature. These results suggest that nutrient and energy depositions follow rational patterns and that simple models can be developed to predict the composition of fish of different sizes (Shearer 1994; Lupatsch *et al.* 1998; Bureau *et al.* 2000).

Shearer (1994) concluded that the protein content of growing salmonid is mainly determined by fish size and genetic factors, that lipid level is affected by both endogenous (fish size, growth rate) and exogenous (dietary, environmental) factors, and that ash content is homeostatically controlled. An effect of diet composition and feeding level on energy gain and carcass composition of rainbow trout has been observed (Rodehutscord & Pfeffer 1999; Bureau *et al.* 2000; Lupatsch, Kissil, Sklan & Pfeffer 2001). Research aimed at the development of models to predict rainbow trout proximate composition at various sizes depending on the composition of the feed fed and growth performance is underway.

(3) Waste estimation

The maintenance of life processes (integrity of the tissues of the animal, osmoregulation, respiration, circulation, swimming, etc.) and the deposition of body components have costs in terms of nutrient and feed energy. Basic and practical research has allowed the development of simple, yet reliable, models (equations) to calculate these costs or wastes. Studies involving the rearing of fish under various conditions (water temperature, feeding level, fish size, etc.) have shown that these biological costs are, surprisingly, fairly constant for a given diet and fish species and, consequently, fairly easily predicted (Azevedo *et al.* 1998; Lupatsch *et al.* 1998; Ohta & Watanabe 1998; Rodehutscord & Pfeffer 1999; Bureau *et al.* 2000; Lupatsch *et al.* 2001).

(4) Ration allowance

Calculation of the ration can be done by simply adding all the different components calculated above (body components deposited + waste produced) per unit of time (day, week) to calculate total cost. This cost is generally expressed as digestible energy (DE). Assuming that a feed is well balanced nutritionally, knowledge of the DE content of that feed generally allows calculation of the amount of feed to be fed or the feeding level to be used. This calculated amount of feed generally represents the minimum amount of feed required to achieve the predicted growth of the fish.

(5) Feeding strategies

Any model, as good as it is, cannot replace common sense when feeding fish and it is up to the producer to determine how much feed to serve and how to serve it depending on the prevailing conditions. Feed should be served in a manner that allows adequate opportunity (time or space-wise) for the fish to consume the determined ration and achieve their growth potential while minimizing feed wastage.

Regardless of the feeding system or method used, accurate growth and feed requirement models can be very valuable management tools since they may allow to forecast growth and objectively determine biologically achievable feed efficiency (based on feed composition, fish growth, composition of the growth). These estimates can be used as yardsticks to adjust feeding practices or equipment, compare results obtained and improve husbandry practices (Cho & Bureau 1998).

Interest in the use of nutritional strategies to reduce waste output and minimize the environmental impact of aquaculture operations has grown tremendously over the past two decades. Very significant improvements in feed quality and feeding practices have been achieved. These have resulted in a significant reduction in waste outputs (per tonne of fish produced) for many types of aquaculture operations. The number of research publications is ever expanding and covers an increasing number of fish species. A number of feed manufacturers have also been leaders in this field. For example, most of salmonid fish feed formulae commercially available nowadays result in significantly less waste outputs than those that were commonly available and used less than a decade or two ago. Nevertheless, significant improvements can still be made, especially in terms of the reduction of P waste output.

Conversely, it is interesting to note that only minor improvements have been achieved in practice for so-called omnivorous warm water fish (catfish, tilapia, carp, etc.). Research scientists, nutritionists, feed manufacturers and farmers have been slow or unwilling to follow or explore the examples set elsewhere. Consequently the use of feeds of low digestible nutrient and energy densities (e.g. low protein and lipid, high carbohydrate feeds), resulting in a high (poor) feed conversion ratio and very significant amounts of SW, is still the norm in the field as well as the research environment. There is reason to believe that the 'omnivorous' fish culture industry could benefit greatly from a move toward higher digestible nutrient density and the application of the other basic nutritional strategies for the management of aquaculture waste reviewed here. Very interesting but often overlooked evidence supporting our view can be found in the literature (e.g. Jantrarotai, Sitasit, Jantrarotai, Viputhanumas & Srabua 1998).

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