Feed management and on-farm feeding practices of temperate fish with special reference to salmonids

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ABSTRACT

Under all aquaculture conditions, feeding practices have economic, environmental and social implications. Even with nutritionally adequate and balanced 'environmentally friendly' feeds, inappropriate feeding practices can lead to significant feed losses causing adverse effects on water quality and decreasing the sustainability of aquatic animal production. Much progress has been made in the production of salmonids through improving nutritional value, feed physical characteristics, and feeding practices in order to optimize feed and nutrient utilization and to reduce potential environmental impacts. There is strong scientific evidence that proper feeding systems and strategies should give due consideration to the behavioural rhythms of the species cultured and the nutritional quality of the diets. There are currently a number of quite sophisticated feed distribution systems for use in salmonid production, their utility depending upon how well they are adapted to the species and size of fish and to the culture site. There are also a number of devices to monitor the feeding activities of salmonids. Modern feeders and feeding schedules have been developed by feed manufacturers based on fish size, water temperature and the energy content of feed, and appropriate directions have been provided to achieve maximum growth and feed utilization under diverse environmental and culture conditions. Most of the progress made with salmonids can be adapted and applied to other temperate marine finfish, as well as to tropical species totally relying on man-made feeds. This includes feed processing technologies as well as on-farm feed management practices and strategies. Accumulating evidence shows that other marine finfish grown in cages as well as tropical fish reared in ponds, can adapt themselves to modern demand feeders. Such devices also hold much promise for understanding the specific feeding rhythms of new species and for obtaining quantitative data on the control of voluntary feed intake as affected by dietary nutrients. Knowledge gained and achievements made in the development of nutritionally wholesome starter feeds, continuous feeding by the use of belt-feeders for rearing larval or juvenile fish, application of bioenergetic principles to develop feeding tables and the use of extruded feeds can and should be applied to tropical aquaculture species.

1. INTRODUCTION

Under aquaculture conditions, feeding practices have economic, environmental and even social implications. Even with nutritionally adequate and balanced 'environmentally friendly' feeds, bad feeding practices can lead to significant feed losses that cause adverse effects on water quality and decrease the sustainability of aquatic animal production. In the present review, the objective is to show the progress made in feed management practices in salmonid aquaculture, taking into account the evolution of the nutritional value and physical characteristics of feeds; recent advances in feeding methods and practices employed to optimize feed and nutrient utilization; and strategies for waste management that are designed to reduce environmental impacts. Since most of the feeding practices and strategies are based on conceptual ideas on the control of feed intake in fish supported by experimental work, some information on such concepts is also provided. It is also becoming clear that most of the progress made with salmonids, with regard to the feed processing technologies and on-farm feed management practices and strategies, can be applied to other temperate marine finfish, as well as to warmwater species totally relying on man-made feeds.

2. PRODUCTION OF SALMONIDS

Over the past three decades, the growth of salmonid production around the world has been high, increasing from about 75 000 tonnes in 1970 to more than 2.4 million tonnes in 2010 (Table 1). This growth is undoubtedly due to the progress made in the areas of fish nutritional science, feed processing technologies, feed development and feed management practices. This increase in production also provides us with abundant information, not only with regard to the physical and nutritional characteristics of feeds but also regarding the management of feeds at the farm level. This review focuses mainly on rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*Salmo salar*), the two major species of salmonids that together make the major contribution to global salmonid production.

TABLE 1

Production of salmonid species over the past four decades (tonnes)

Species	1970	1980	1990	2000	2010
Atlantic salmon (*Salmo salar*)	294	5 288	225 642	895 808	1 425 968
Rainbow trout (*Oncorhynchus mykiss*)	64 741	145 124	277 815	491 927	728 448
Coho salmon (*O. kisutch*)	250	2 560	39 164	108 626	137 510
Sea trout (*Salmo trutta trutta*)	1 470	2 270	4 888	6 937	24 017
Chinook salmon (*O. tshawytscha*)	0	0	14 998	16 664	13 541
Arctic char (*Salvenilus alpinus alpinus*)	0	0	69	1 093	3 156
Ayu sweetfish (*Plecoglossus altivelis altivelis*)	3 197	7 898	13 017	9 324	6 484
Trouts nei[1]	759	3 352	11 202	12 632	17 949
Whitefishes nei[1]	4 400	5 800	1 562	2 233	4 284
Others	0	0	802	1 751	49 780
TOTAL	**75 111**	**172 292**	**589 149**	**1 546 995**	**2 411 137**

Note: [1]nei = not elsewhere included.

Source: FAO (2012).

3. EVOLUTION OF NUTRITIONAL PROFILES OF FEEDS

Since the farming of salmonids is totally dependent on formulated feeds, these are formulated to supply all the essential nutrients and energy in tune with the needs of the animal for the maintenance of vital physiological functions, such as growth, reproduction and health. An additional imperative in aquaculture, especially with regard to salmonids, is that of ensuring both environmental quality and the nutritional value of the fish produced, both of which are related to the nutritional quality of the feeds used.

Because the nutrient requirements for all the species under aquaculture are not known and are difficult to determine, it is common practice to extend data from more or less closely related species. This is very much the case with regard to salmonids as a group. Based on studies undertaken with juvenile rainbow trout grown in freshwater, relatively complete knowledge has been gained on the quantitative needs of rainbow trout with regard to all the essential nutrients (Cho and Cowey, 1991; Hardy, 2002). In contrast, despite the high level of production of Atlantic salmon at a global level, the nutrient requirements of this species are not so well defined as for rainbow trout. The limited information available is based on studies undertaken with small fish grown in freshwater, before the parr-smolt transformation, after which they are grown in the sea. In the absence of specific data on their nutrient requirements, information gathered from other salmonids, such as rainbow trout and Pacific salmons is extended and applied to develop feeds for Atlantic salmon (NRC, 1993; Storebakken, 2002).

Early feeds for salmonids were rich in protein and low in energy content. One major change that has occurred over the past 30 years is the shift from feeds with relatively high protein content (>50 percent) and low total lipid level (12 percent) to feeds that are lower in protein content and higher in lipid levels (Hardy, 2002; Storebakken, 2002). Much attention has been paid to developing high-nutrient and energy-dense feeds (Cho *et al.*, 1991; Bureau, Kaushik and Cho, 2002). Current feeds have high digestible energy levels thanks to the use of extrusion technology that allows the inclusion of high levels of oil. At the same time, instead of reasoning in terms of crude protein levels, close attention is now given to the digestible protein levels.

In recent years, one major concern has been the relatively high dependence of salmonid feeds on fishmeal and fish oil, which are finite sources whose use raises questions regarding their future availability and cost. Thus during the past decade much effort has been directed towards replacing the high levels of fishmeal and fish oil in the feeds for Atlantic salmon and rainbow trout. Based on data provided by Tacon, Hasan and Metian (2011), we can see that although the feeds for salmonids (salmons and trouts) represent 9 percent of the aquafeeds used globally, the production of salmonids necessitates the use of over 19 percent of all of the fishmeal and nearly 51 percent of all of the fish oil used by aquaculture (Table 2).

TABLE 2

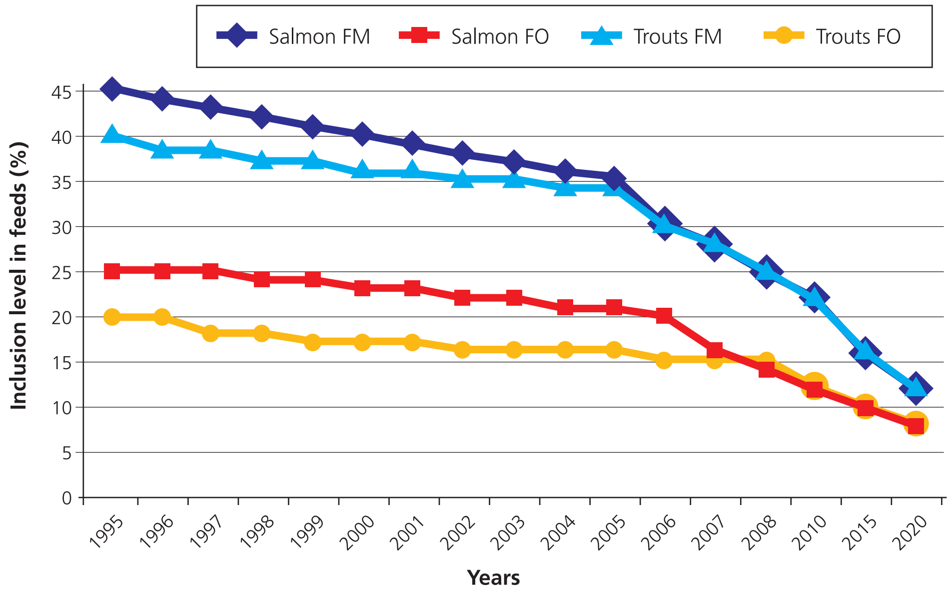
Projected use of feeds, fishmeal and fish oil for the production of salmonids in 2010

	Production (tonnes)	Feeds used (tonnes)	Fishmeal used (tonnes)	Fish oil used (tonnes)
Salmons	1 734 000	2 225 000	496 000	271 000
Trouts	746 000	970 000	213 000	116 000
Total salmonids	2 480 000	3 195 000	709 000	387 000
Total all fed species	21 201 000	35 371 000	3 670 000	764 000
Salmonids, % of total	11.7	9.0	19.3	50.7

Source: Tacon, Hasan and Metian (2011).

Over recent decades, significant efforts have been made by the salmonid industry to reduce the levels of inclusion of fishmeal and fish oil (Figure 1). Watanabe *et al.* (1998) demonstrated that rainbow trout could be grown over long periods with properly balanced non-fishmeal diets, even without any supplementary indispensable amino acid (IAA) Similarly, Kaushik *et al.* (1995) found that total replacement of fishmeal with alcohol-water extracted soy protein concentrate adequately supplemented with methionine led to similar growth and nitrogen utilization, compared to fish fed a fishmeal-based feed. Mambrini *et al.* (1999) showed that soy protein concentrate could replace 50 percent of fishmeal in high-fat extruded diets for rainbow trout. Similar success has not been reported in other salmonids, such as the Atlantic salmon or the Pacific salmons, for high levels of substitution of fishmeal, even by protein-rich soybean products (Kaushik, 2008). However, with mixtures of plant protein sources that are properly selected and adequately supplemented with amino acids and in the absence of antinutritional factors, there is much potential for replacing high levels of fishmeal in the diets of most fish (Kaushik and Hemre, 2008) including rainbow trout, Atlantic salmon (Espe, Lemme and El-Mowafi, 2006) and other marine finfish such as European seabass (*Dicentrarchus labrax*) (Kaushik *et al.*, 2004) and gilthead seabream (*Sparus aurata*) (de Francesco *et al.*, 2004; Sitja-Bodadilla *et al.*, 2005). A major difference between Europe and other countries in this particular area is that terrestrial animal by-products (processed non-ruminant animal proteins) are not utilized by feed companies and farmers, whereas in other parts of the world their use does not raise any serious concern.

FIGURE 1
Changes in the inclusion of fishmeal (FM) and fish oil (FO) in the feeds for salmonids over recent decades and predicted further reductions



Source: Adapted from Tacon, Hasan and Metian (2011).

Given that high energy feeds for salmonids are rich in total lipid levels and that this has mainly been supplied through fish oil, there has also been significant interest in substituting the fish oil with other lipid sources. Much progress has been made in this regard in both Atlantic salmon and rainbow trout, and studies have clearly shown that in feeds containing some of fishmeal, additional fish oil can totally be replaced by single vegetable oils (i.e. rapeseed, soybean, linseed) or a mixture of vegetable oils. The changes in flesh fatty acid profiles that are bound to occur can be re-tailored, to meet human nutritional needs or demands, by a period of finishing with fish oil-rich feeds (Bell *et al.*, 2004; Richard *et al.*, 2006).[1] More recently, combined reduction in both fishmeal and fish oil levels in feeds for Atlantic salmon (Tortensen *et al.*, 2008), rainbow trout (Panserat *et al.*, 2009) and gilthead seabream (Benedito-Palos *et al.*, 2007) has been demonstrated through concerted efforts between various research groups.[2]

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[1] Also see: www.rafoa.stir.ac.uk

[2] See, for example, www.aquamaxip.eu

The salmonid feed industry has thus undergone significant changes over the past 30 years by taking into account the progress in fish nutrition science, the technological advances in the feed manufacturing sector, the economics (by developing least-cost formulae) and the environmental consequences (by developing nutrient-dense, highly digestible, environmentally friendly feeds). In recent years, the industry has also been confronted with food safety issues and has taken adequate measures to reduce all potential feed-borne contaminants. This movement from least-cost towards least-risk is taken a step further by also considering all possible environmental burdens associated with such feeds (Papatryphon *et al.,* 2004).

4. EVOLUTION OF THE PHYSICAL QUALITY OF FEEDS FOR SALMONIDS

The global production of feed for salmonids in 2010 is estimated to range between 3.05 and 3.23 million tonnes (Tacon, Hasan and Metian, 2011; FAO, 2012). Feeds for rainbow trout and other salmonids have undergone major changes since the 1960s: from trash fish/terrestrial animal by-products through semi-moist feeds to dry pelleted feeds and to extruded high-nutrient and energy-dense feeds.

In the early days of salmon and trout farming, it was common to use trash fish as feed, with or without additional mixtures to supply other micronutrients and facilitate binding. It was also common to use moist feeds based on terrestrial animal by-products (bovine liver or spleen), along with trash fish or fish offal mixed with grains, milk products, bread, etc. The first nutritionally complete diets appeared about 1955 (Rumsey, 1994), which led to some of the pioneering works on the nutrition of salmonids. From a practical point of view, by the 1970s, the first ever dry feeds were formulated and developed for growing salmon (Pacific and Atlantic) and trout (EIFAC, 1971; Fowler and Burrows, 1971; Fowler, Banks and Elliott, 1972; Luquet, 1972). Semi-moist feeds, such as the ‘Oregon moist pellet’, were also being used initially and comparisons to dry pellets made to see the differences in efficacy of such moist pellets (Clark and Langmo, 1980). At some stage, feeds based on acid-preserved silage from fish offal were also promoted (Raa and Gildberg, 1982). Experimental studies have shown that it is possible to grow salmon over long periods with such semi-moist diets containing acid-preserved fish silage (Jackson, Kerr and Cowley, 1984; Dumas *et al.,* 1991). However, the economic viability of such practices remains to be demonstrated under practical farming conditions.

Another option is the production of a moist feed prepared from alkaline-preserved (pH 11.2) herring filleting by-products mixed with a crude binder based on seaweed. The mixture is then pelleted and immersed in an acidic bath to obtain the proper gelatinization characteristics. Studies undertaken with Atlantic salmon on the use of such moist feed appear to show promising results in terms of digestibility, growth and feed efficiency (Sorensen and Denstadli, 2008). Some studies have also attempted to make direct use of fish offal or trash fish by combining microwave and extrusion technologies, as a measure of waste recycling with the possibility of producing feeds containing up to 47 percent crude lipid (Hemre and Sandnes, 1999). The use of such moist pellets is also practiced in some cases, mostly for experimental purposes for evaluating the effects of different alternative sources (Hardy, Scott and Harrell, 1987; Waagbo *et al.,* 1994; Morkore and Austreng, 2004).

The adverse effects of moist and semi-moist feeds on feed stability and on environmental quality are generally recognized (Cowey and Cho, 1991), and all salmon and trout farmers now rely exclusively on nutritionally complete dry feeds right from first feeding throughout the production and reproductive cycles.

There are also differences between the feed processing techniques used in fish nutrition research and in practical feed trials. For the determination of nutrient requirements, for instance, purified ingredients are often blended with water, made into a ‘spaghetti’ and kept either frozen or dried and then crumbled before use.

Dry or steam pelleting is also used for experimental purposes. Dry pelleting, which is easily applicable in the animal feed industry, is done either with or without preconditioning, but cannot achieve lipid levels above 13 to 15 percent. Some double pelleting techniques can be used to reduce fines and increase pellet stability and lipid content. For almost two decades, extrusion technology, although more expensive and technically demanding than the conventional dry pelleting process, has been the major processing method for the production of salmonid feeds. Extrusion and, to a lesser extent, expansion techniques that are used for the manufacture of feeds for salmonids differ significantly in terms of heat as well as mechanical treatments (Table 3).

TABLE 3

Thermal treatments and duration of treatment for different feed processing methods

Process	Temperature (°C)	Duration (seconds)
Pelleting		
short conditioning	60–90	25–35
long conditioning	60–95	70–250
Expansion	80–140	5–15
Extrusion	80–200	30–150

Source: Melcion and van der Poel (1993).

From a nutritional point of view, extrusion and expansion processes are known to improve starch digestibility of cereals (Bergot and Brèque, 1983) and consequently lead to increased digestible energy levels. Even with pulses such as peas and lupins, extrusion can increase the digestibility of starch (Burel *et al.*, 2000). Extrusion is also known to decrease the levels of antinutritional factors and bacterial counts in the finished feeds (Melcion and van der Poel, 1993).

Extrusion technology offers flexibility in improving the use of cereals and can improve the physical characteristics of the finished feeds, with reduced levels of fines and greater water stability. A simple reduction in the amount of fines in the feed significantly improves suspended matter release in the aquatic environment while improving feed efficiency. However, depending on the raw material matrix, significant differences can be observed in terms of the physical characteristics of the feeds (Table 4).

TABLE 4

Some physical characteristics of pelleted and extruded fish feeds made with identical ingredient mixtures

Feed Mixture	A1		B2	
Feed Processing Technology	Pelleted	Extruded	Pelleted	Extruded
Mass/Volume (g/L)	612	580	633	504
Durability (Mechanical, Pfost) (%)	87	100	93	99
Durability (Pneumatic, Holmen) (%)	25	97	70	94
Floatability (% residues at 30 seconds)	0	0	0	10
Sinking rate (cm/second)	8	6.2	9.7	4
Water stability (% residues at 10 minutes & 1 hour)	30 / 89	0 / 4	17 / 37	11 / 92
Slope of particle breakdown (10–60 minutes)	0.0114	0.0097	0.0052	0.0167
Oil absorbing capacity (%)	16	18	16	31

Notes: [1] A: Basal diet containing fishmeal, fish oil, gelatinized starch, vitamin & mineral mixtures; [2] B: 80% A + 20% wheat gluten.

Source: Unpublished data of S.J. Kaushik and J.P. Melcion.

The advent and systematic use of extrusion and expansion techniques has made it possible to manufacture feeds with specific physical characteristics, such as increased stability and less fines, and to tailor buoyancy and nutritional profiles, such as the reduction of antinutrients and above all the possibility to increase the fat level in the feeds to increase digestible energy levels. Indeed, most extruded pellets are top-dressed or vacuum-coated with oils to achieve penetration of the oils into the feed and to reach final fat levels of 30 or even 40 percent. Certain heat-labile nutrients such as ascorbic acid and astaxanthin, feed attractants and other additives are also post-coated once the extrusion process is over. Water stability of feeds is not a major issue for salmonids, as both rainbow trout and Atlantic salmon generally consume feeds very quickly after delivery into the water without much loss of nutrients through leaching. However, in cases when lipid is not properly top-coated on the extruded feed pellets, a thin layer of oil may be observed on the water surface.

In both Atlantic salmon and trout, broodfish are grown in freshwater in land-based farms where they are fed broodstock feeds that are generally rich in long-chain polyunsaturated fatty acids supplied by fish oil and enriched in vitamins (C or E). In the initial stages, broodstock used to be fed moist-feeds comprising herring, sardines or smelt depending on local availability. Very soon, formulated dry feeds were developed and these are currently used in all cases.

Eggs are stripped from females and the milt collected from males is used to fertilize the eggs. Salmonid eggs, which are normally between 5 and 8 mm in diameter, have a long incubation period of about 400 to 500 degree days. At hatching, the free-swimming larvae weighing about 100 mg are fed complete feeds of small particle size (300 to 600 µm diameter). Starter feeds for first-feeding alevins and fry are made by crumbling extruded pellets. Other techniques, such as cold-extrusion using a spheronizer or marmurizer, render it possible to produce feeds with uniform spherical particles of small sizes suitable for first-feeding fry or fingerlings. Such feeds are generally rich in protein and low in total fat content.

5. FARMING PRACTICES

Rainbow trout are mainly grown in freshwater, although a small quantity is also produced in sea cages. In most land-based farms, rainbow trout are grown in raceways, generally of concrete construction and with a continuous supply of freshwater from a river system or natural underground spring, and the effluent water is released back into the river after sedimentation of suspended solids. Depending on the source of water supply, water temperature in these farms will either follow the natural seasonal changes in river temperature or be constant, in the case of water drawn from natural springs. Water flow rate and several physicochemical characteristics can vary depending on season.

After hatching, both rainbow trout and Atlantic salmon are grown in tanks or basins supplied with freshwater. For Atlantic salmon, prior to transfer to the sea, specific feeds containing salt, betaine, nucleotides and other supplements are used in order to improve the osmotic balance of fish undergoing smoltification. In the marine environment, salmon are reared in cages, the dimensions of which vary considerably, and depend solely on formulated feeds. Depending on the size and stage of the life cycle, the feed utilized varies in particle size and nutrient profile (Table 5).

TABLE 5

Pellet particle size used for different sizes of Atlantic salmon and rainbow trout, with crude chemical composition of the feeds

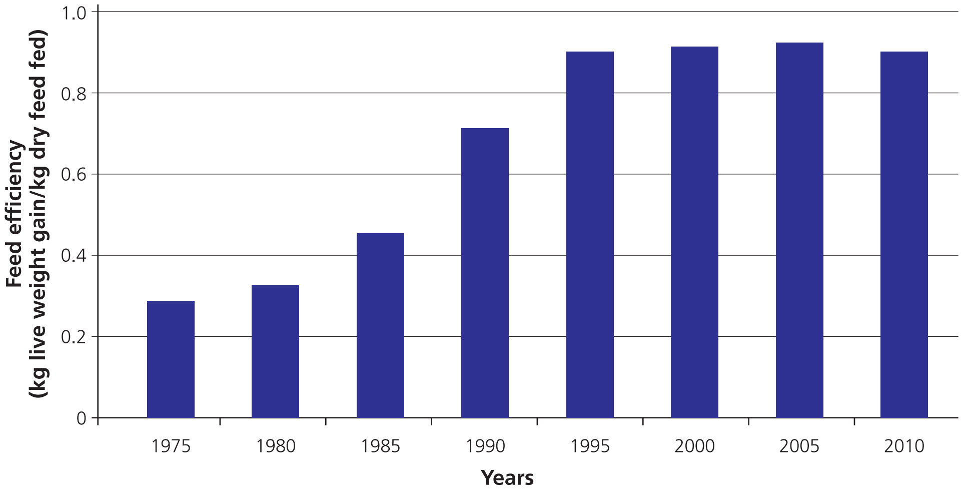
Fish body weight BW (g)	Particle diameter (mm)	Crude protein (%)	Crude lipid (%)	Digestible energy (kJ/g)
<0.3	0.3	50–55	18	18–19
0.3–0.8	0.5	50	18	18–19
0.8–1.5	0.8	50	20	19–20
1.5–5	1–1.2	50	20	19–20
5–10	1.5–1.8	50	20	19–20
10–30	2	45–50	22	19–20
30–100	3	48–50	24–26	19–20
100–250	4	46–48	26–28	19–20
250–500	5	44–46	28–30	20–21
500–1 000	6	44–46	28–30	20–21
1 000–2 000	7–7.5	42	30–32	21–22
2 000–3 000	9	40	30–32	21–22
>3 000	11	40	30–32	21–22

Source: Compiled data from commercial feed companies.

The improved physical and nutritional characteristics of extruded feeds have led to significant beneficial effects in terms of fish growth and feed efficiency in salmonids (Figure 2).

FIGURE 2

Improvement in feed efficiency in Atlantic salmon production 1975–2010



Source: Myrseth (2005) and unpublished data of S.J. Kaushik.

5.1 Feed choice, availability, transportation and storage

All salmonid farmers use commercial feeds purchased from dedicated feed manufacturers. Three major feed manufacturers supply almost 80 percent of the feeds for salmonids. Some salmon farming companies have their own feed manufacturing facilities as part of vertical integration. Currently, no farmers resort to on-farm feed production, but in a few cases farmers can make small amounts of speciality feeds (e.g. medicated feeds) using various kinds of mixers to mix such additives with the commercial feeds they purchase.

Feeds are manufactured by commercial companies and are continuously made available throughout the year. Depending on demand, feed is delivered by trucks for farms on land or by dedicated boats to the cage-farm sites. There are even special feed delivery vessels such as ‘silos to silos’ supplying feeds directly from the factories to the cage farms. Feeds are delivered in small bags of 25 or 60 kg, in large bags of 500 kg or 1 tonne or in bulk, depending on the volume of purchase and the type of feed. On reception at the farm sites, feeds are stored in dedicated ventilated storage rooms or in large silos (Figure 3) where they are stored for long periods.

Feed labelling is also an important issue. Currently in Europe most, if not all, salmon and trout feeds are described in sufficient detail through labels giving both ingredient and major nutrient composition. Such labels or the accompanying documents also clearly provide information on the conditions and duration of storage.

FIGURE 3
Feed silos at a land-based freshwater rainbow trout farm

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5.2 Feeding methods

In parallel with advances in formulating adequate feeds and in processing technologies for producing feeds of diverse nature that meet the demands of fish, efforts have also been directed towards the improvement of on-farm feed management practices. Research towards understanding the underlying physiological mechanisms involved in the control of voluntary feed intake and feeding rhythms or patterns, as affected by environmental factors including nutrition, have provided valuable information (Houlihan, Boujard and Jobling, 2001) on this topic. As with all poikilothermic animals, feeding schedules for rainbow trout and salmons vary with water temperature. Voluntary feed intake also varies with the body mass of fish, small fish consuming more per unit body mass than larger fish.

5.2.1 Feed distribution by hand

On land-based farms such as raceways, rainbow trout are most often fed by hand (Figure 4). Hand-feeding is also practiced for rearing broodfish, using semi-floating pellets in order to closely monitor feed intake. Hand-feeding is also practiced in the rearing of Atlantic salmon in small farms. Hand-feeding requires a clear idea of how

FIGURE 4
Hand-feeding is commonly practiced in the rearing of rainbow trout in raceways

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much feed is to be distributed to a given tank or cage. This is generally done by using feeding tables provided by the feed manufacturers themselves (Table 6) or by the farmers developing their own feeding tables based on past experience and observation. One recognized advantage of such hand-feeding is the capacity of the farmer visually to observe the feeding behaviour of the fish stock and adjust the quantity of feed to be distributed accordingly.

TABLE 6
An example of a feeding table for Atlantic salmon (% BW/day)

Body weight (BW) (g)	4° C	8° C	12 °C	16 °C	18 °C
Freshwater phase					
<0.3	ad libitum				
0.3–0.8	2.0	3.0	4.0	4.5	4.5
0.8–5.0	1.8	2.7	3.5	3.9	3.9
5.0–10.0	1.6	2.1	3.1	3.4	3.4
10.0–25.0	1.4	2.0	2.7	3.1	3.0
25.0–40.0	1.0	1.6	2.2	2.7	2.6
40.0–60.0	1.0	1.3	2.0	2.6	2.5
Seawater phase					
80–200	1.5	1.9	2.2	2.8	
200–300	1.3	1.9	2.3	2.6	
300–500	1.2	1.7	2.0	2.3	
500–775	1.0	1.4	1.7	2.0	
775–1 000	0.8	1.0	1.5	1.8	
1 000–1 250	0.7	1.0	1.3	1.5	
1 250–1 500	0.6	0.9	1.2	1.4	
1 500–2 000	0.5	0.7	1.1	1.2	
2 000–3 000	0.5	0.7	0.9	1.1	
>3 000	0.5	0.6	0.9	1.0	

Source: unpublished data of S.J. Kaushik.

It is now established that trout and salmon fry should be weaned with starter feeds as soon as possible after their mouths become open. First-feeding fry are generally fed almost continuously, which requires the use of some kind of a feeding device. Utmost care is taken at this stage to maintain water quality and to avoid excessive feeding with too fine particles, which can adversely affect gill ventilation and filtering.

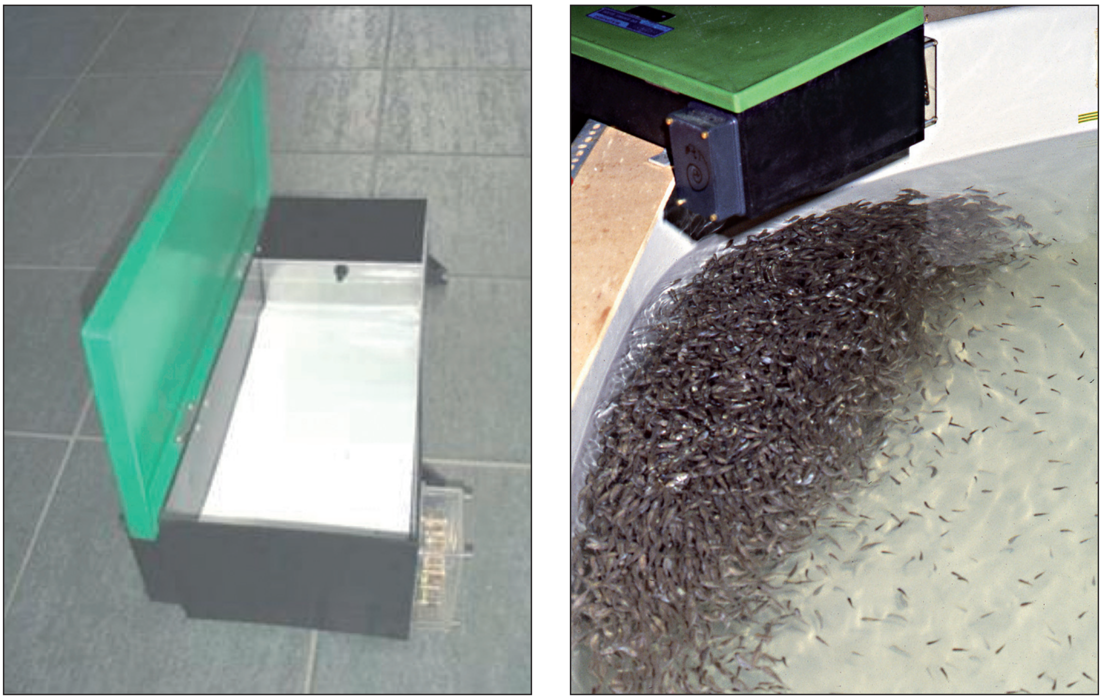
There are currently a number of quite sophisticated feed distribution systems for use in aquaculture. The choice will depend upon how well they are adapted to the species and size of fish being raised and to the culture site.

5.2.2 Belt-feeders

Belt-feeders are mostly utilized for the rearing of small fish (Figure 5). A given amount of feed is placed on a belt which slowly moves, dropping feed into the rearing tanks or basins. Feed is slowly and evenly released into the tanks. These feeders use a clockwork mechanism and are thus easy to use even in remote areas, since no electric power is required. The belt is pulled back to initiate functioning of the clock. The desired amount of feed is spread over the belt surface, either all along the belt or in clumps. These feeders can deliver between 3 and 5 kg of feed per tank, operating over either 12 or 24 hours to deliver feed over the full 24 hours of the day or only during the photophase (i.e. during daylight). Electrically operated belt feeders are used in indoor hatcheries.

FIGURE 5

Belt-feeder based on a clock-work mechanism used for rearing young fish (left: an empty belt-feeder and right: feed being delivered from the feeder)



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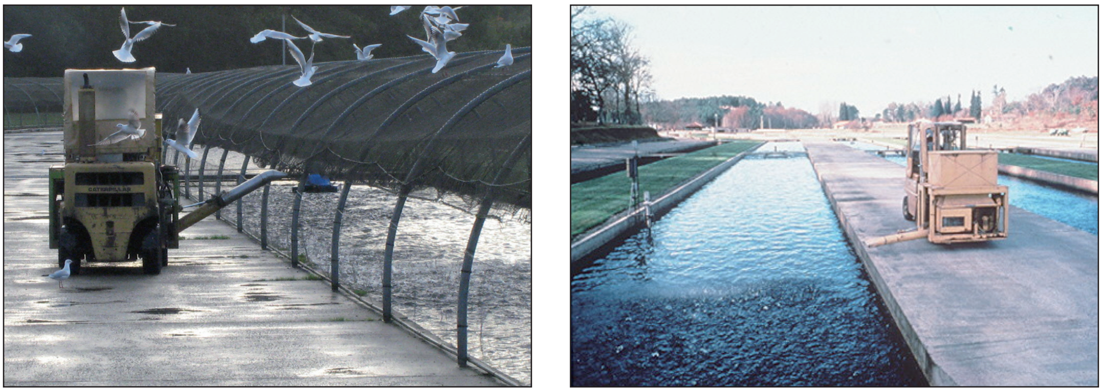
5.2.3 Mechanical feeders

Several types of automatic and mechanical feeders are available for trout farming, including electric, water-powered and solar-powered units with variable timers. There are feeders that use compressed air to blow feed out over the water surface at preset intervals, and truck or trailer mounted units that blow the feeds into the tanks

(Figure 6). Mechanical feeders based on vibrating systems deliver small quantities of a given amount of feed per delivery, the frequency of which can be adjusted. These are generally used for rearing small fish.

FIGURE 6
Two examples of mechanical delivery of feeds in a land-based rainbow trout farm



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5.2.4 Demand feeders

Demand feeders are widely used in freshwater rainbow trout farms (Figure 7), as well as on small cage sites for salmon farming (Figure 8). Feed is placed in cylindro-conical bins and below the feed container, a movable disc is attached and a pendulum or a rigid rod extends to, or somewhat below, the water surface. The disc acts as a plug to prevent feed from falling out of the bottom of the feeder. When a fish swims around and moves the pendulum, the disc is shifted and a small quantity of feed is delivered. There are several variants of the self-feeding trigger: fixed rod (as mentioned above), 'bite and pull' and even photosensitive triggers placed just below the surface of the water, the relative advantages or inconveniences of which are continuously being studied.

The amount of feed delivered with each movement of the rod is adjusted by positioning the disc vertically up or down the rod, resulting in a larger or smaller amount of feed delivery. Fixed-rod triggers can be placed just below the water surface, but accidental collisions with the trigger can increase feed wastage. This is prevented by enclosing the rod in a protective screen or placing the trigger just above the water surface. Generally, salmonids, and especially rainbow trout, learn to use the rods very quickly in order to get the reward.

The original studies on the capacity of fish to use self-feeders were undertaken nearly 50 years ago using goldfish as a model (Rozin and Mayer, 1961, 1964). Fish fed using demand feeders often display highly variable feeding activity, both within a day and across days. In rainbow trout and salmon, significant peaks in trigger-biting activity occur at dawn and dusk (Kadri *et al.*, 1991; Boujard, 1999). Depending on gastric evacuation rate and the return of appetite, peaks in trigger-activation activities can vary across days.

Studies have also been undertaken to understand the feeding activity and behaviour, especially with regard to the detection of differences in trigger activation by individual fish within a batch, using individually tagged fish or video observations. In some cases, after a few days of acclimation to the system, only one or two individuals account for almost all of the trigger-biting activity. Development of a dominance hierarchy, in which the dominant individuals monopolize the trigger and consequently grow better than the others within the group, has been observed in

FIGURE 7
A demand feeder used in a rainbow trout farm

COURTESY OF G. CHOUBERT, INRA.

FIGURE 8
A demand feeder used in the rearing of salmon in cages

COURTESY OF FAO/S.J. KAUSHIK.

the arctic char (*Salvelinus alpinus*) (Brännäs and Alanärä, 1993). However, whether or not this is a common phenomenon is not clear, since there appears to be much variation in feeding behaviour depending on the level of domestication of the species concerned. It is also reported that fish fed using demand feeders often display variable feeding activity over time. Bailey and Alanärä (2006) found that this variability was very much linked to differences in gut evacuation rates and the return of appetite.

Demand feeding systems have the advantage of taking into account the behavioural rhythms of the fish and the nutritional quality of the diet. There is accumulating evidence to show that other marine finfish grown in cages, as well as tropical fish reared in ponds, can adapt themselves to such demand feeders. Such devices also hold much promise for understanding the specific feeding rhythms of new aquaculture species and for obtaining quantitative data on the control of voluntary feed intake (VFI) as affected by dietary nutrients. The other benefit of demand feeders is that fish feed themselves according to their endogenous rhythms, resulting in low labour costs and little waste of feed, provided that the feeding device and the trigger are adjusted properly. Proper adjustment can also reduce aggressiveness within a group, reducing size variability.

5.2.5 Computer-controlled automatic feeding systems

Other types of mechanical feeders used in salmon and trout farming involve the use of tubes extending from feed bins or silos to each tank or sea cage. In land-based farms, these tubes are rigid structures that are permanently fixed to the tank or basin sides (Figure 9). For rearing trout or salmon in floating cages, such tubes are made of flexible material that floats on the water, connecting each cage to the feed storage bin (Figure 10). These devices have a balance for weighing a given amount of feed coming from the feed bin, and air pressure is used to blow the precise amounts of feed to each cage based on schedules defined by the farmer. In some farms, water instead of air is used as a vector to blow the feeds into the respective tanks or cages.

A number of developments have been made in automatic feed dispensing systems, especially with regard to the control of feed intake and the reduction of feed losses, using relatively sophisticated video sensors and computer-controlled feed delivery systems (Kadri and Blyth, 1997). Further innovations include pellet sensors allowing for feeding fish to satiety without any human intervention, delivering the correct amount of feed and especially avoiding as much as possible any uneaten feed.[3] Automatic feeders equipped with video monitoring systems or infrared sensors (Figures 11 and 12) have been tested extensively under both laboratory conditions (Kadri *et al.*, 1991) and field situations of cage rearing of Atlantic salmon and rainbow trout. Data of Noble *et al.* (2007a) under cage-culture conditions show that Atlantic salmon parr may shift their daily feeding rhythms with season, exhibiting a morning peak in late summer and a midday peak in winter. Using self-feeders with specific devices, these authors could show that daily ration varied between day and season, decreasing from autumn to winter and increasing in spring, and that this was related to both temperature and change in day length.

FIGURE 9
Feed distribution using an automatic feed delivery system in a land-based rainbow trout farm where feed is blown along with water

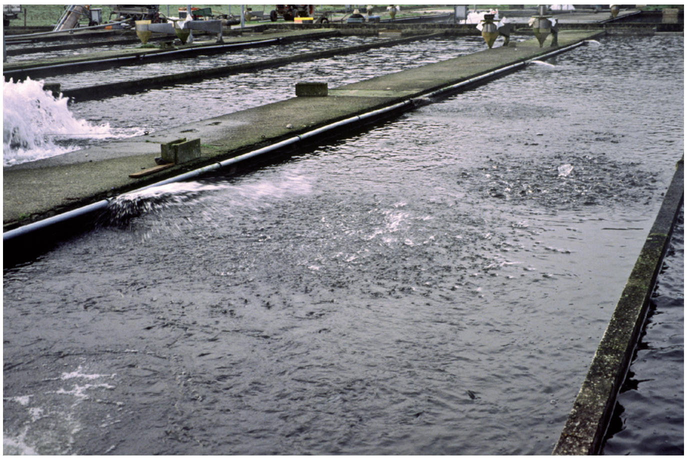

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FIGURE 10
Feed distribution using an automatic feeder for cage culture of Atlantic salmon near Bodo in Norway

COURTESY OF TREVOR TELFER, UNIVERSITY OF STIRLING.

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[3] www.akvagroup.com/index.cfm?id=202454

From a scientific point of view, the self-feeding capacity of fish gives us the opportunity to determine feed preferences, not only as a direct function of palatability of feeds but also as influenced by the physiological status and environmental conditions of the fish. In any case, a diet should cover not only the nutrient requirements but should also be palatable and ingested in sufficient quantities to ensure optimal growth. Maximum growth and feed conversion depend on avoiding over- and under-feeding of fish. Feeding in excess of voluntary appetite causes waste, environmental pollution and higher feed conversion ratios (FCR).

FIGURE 11
Infrared sensor-based feeding control system

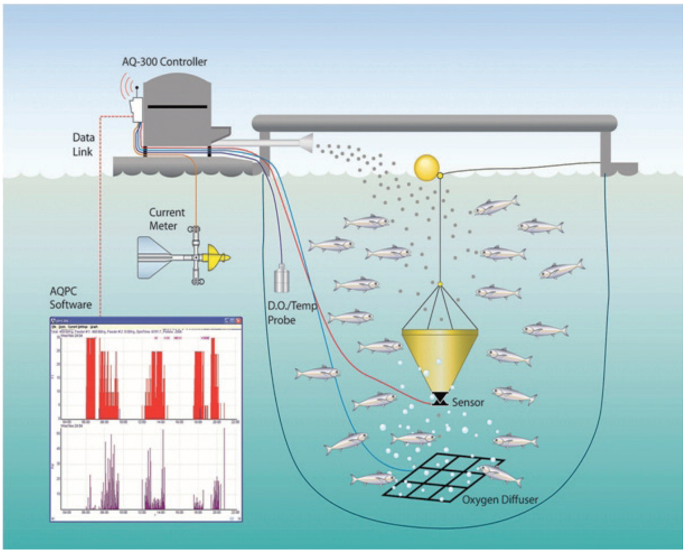

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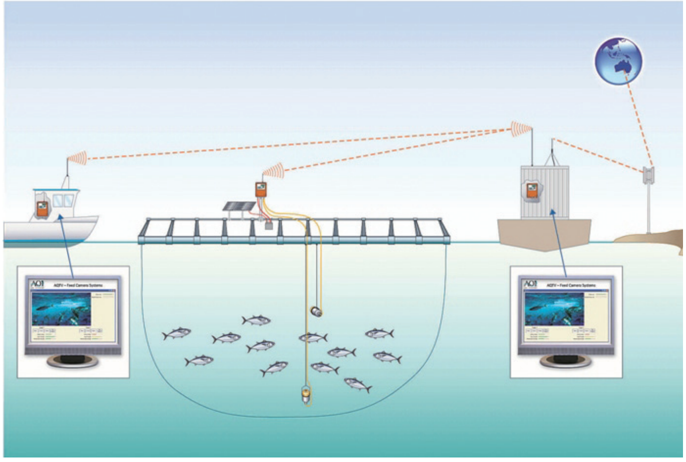
FIGURE 12
Digital feed camera systems



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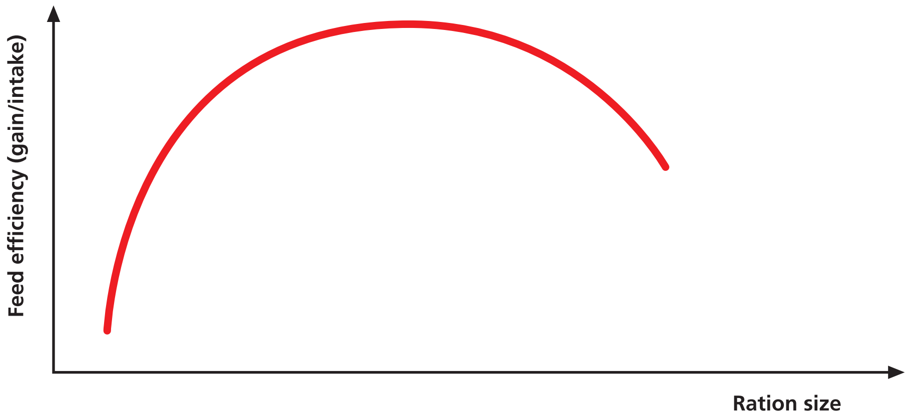
6. DERIVING FEEDING TABLES, FREQUENCIES AND SCEDULES

6.1 Feed allocation

Since growth strongly depends on the amount of feed supplying all the essential nutrients and energy, maximum growth rate is attained by feeding fish at satiation level. When access to feed is restricted or the ration size is reduced, increased size heterogeneity due to social hierarchies appears within the group (Jobling, 1983; McCarthy, Carter and Houlihan, 1992; Brännäs and Alanärä, 1993; Houlihan, Boujard and Jobling, 2001).

Under- or over-feeding, on the other hand, can lead to reduction in feed efficiency (Figure 13). From a practical point of view, in order to optimize ration levels, fish farmers generally rely upon feeding charts provided by feed manufacturers (Table 6; NRC (1993). Often, the farmers themselves empirically derive feeding charts, generally by predicting weight gain and assuming feed efficiency levels based on past history of farm husbandry and performance. A special caution is always issued with such feeding charts stating that they are applicable to a given type of feed and that adjustments will have to be made depending on the type of feed, husbandry conditions, genotype and other environmental factors. Feeding standards should be based on energy and nutrient requirements (Cho, 1992).

FIGURE 13
Theoretical relation between ration size and feed efficiency



Source: Kaushik (2000).

During the last 20 years, proposals have been made to derive specific feeding charts based on nutritional bioenergetic principles. The underlying principles have been detailed in a number of papers (Cho and Kaushik, 1990; Cowey and Cho, 1991; Cho, 1992; Cho and Bureau, 1998). The first condition is that for each species, precise growth prediction is made under given temperature conditions, using temperature growth coefficients for that particular species or genotype. Based on the expected weight gain over a period of time, the expected whole body nutrients and energy gain (RE = retained energy) is determined. Based on the predicted weight gain, allocation of expected maintenance energy requirements (HEf = heat expenditure under fasting) as affected by water temperature and body mass are determined. The energy expenditure due to feed intake (HiE = heat increment of feeding) is calculated. The non-faecal or metabolic energy losses are estimated (retained energy – maintenance need – heat increment of feeding). The minimum digestible energy (DE) required to achieve this growth and body composition is then estimated. Once the DE needs are known, the feed allowance can be made, provided data on the DE levels of the feeds are available. The basic idea behind this concept is that the voluntary feed intake (VFI) is driven by DE needs. Recent research data strongly suggest that this general principle is also applicable to different finfish and to a certain extent, also to shrimp. For salmonids, computer software to estimate feed requirements and to devise feeding tables based on such bioenergetic principles have been developed (Cho and Bureau, 1998) and models developed (Cho, 2004). Such procedures have also been validated with non-salmonids (Kaushik, 1998). The general principles are given in Table 7.

TABLE 7

Evaluation of DE and feed requirements

Evaluate Thermal Unit Growth Coefficient (TGC)	TGC = ($W_f^{1/3} - W_i^{1/3}$) / sum degree days (= T x days)
Predict weight gain (WG)	WG = ($W_i^{1/3}$+ (sum degree days x TGCs)^3
Predict Retained Energy (RE)	RE = ($W_f - W_i$) x %DM x kJ per g DM
Maintenance energy needs (Hef)	
(Hef, in fasting fish, kJ day-^{1}), example for trout	HEf = [(–1.04+3.26*T–0.05*T2)*kgBW$^{0.824}$]
Heat increment of feeding (HiE)	HiE= HEf x O.6
Non-faecal energy losses (NFE)	NFE = (RE+HEf+HiE) x 0.06
Calculate total Digestible Energy needs	(DE) DE = RE + HEf + HiE + NFE
Calculate feed required	Feed = DE needs x dietary DE-^{1}

Notes: W_f = final body weight; W_i = initial body weight; DM = dry matter; T= temperature in °C; BW = body weight; DE = digestible energy.

Source: Based on Cho (1992) and Kaushik (1998).

Such principles are also being applied by feed companies to devise feeding tables and by well-trained farmers for application in the field. In the absence of data on dietary DE levels and on DE needs per unit gain of a given species, a very practical alternative is to let the fish eat to satiety by themselves, using demand feeders.

6.2 Frequency of feeding

It is recognized that all fish should be fed to apparent or visual satiation. The frequency of feeding is governed by two major factors, both of which affect the rate of passage of foodstuffs through the digestive tract (Elliott, 1982). With increasing water temperature, the transit rate is increased and so is the feeding frequency. With increasing body mass/length increment, the transit rate is reduced and consequently, the frequency of feeding is reduced. Thus for first-feeding fish, the feed is provided continuously over the day. Subsequently, as fish grow, the frequency is reduced to eight times per day. Once fish reach 1–2 g, feeding frequency is often brought to four to five times per day, moving to three times per day when fish reach ~5 g. Studies with different salmonids have shown that above 20 g body mass and under standard environmental temperature conditions, a feeding frequency of twice a day to apparent satiation is sufficient (Luquet, Renou and Kaushik, 1981). Even under maintenance conditions, the frequency of feeding can affect nitrogen and energy utilization (Kaushik and Gomes, 1988).

If the feed allocation is insufficient, increasing the number of meals does not bring any further advantage. For instance, in post-smolt Atlantic salmon, increasing the feeding frequency to up to 80 times per day while keeping the daily food ration fixed does not seem to give any better growth rate or any decrease in size variation (Thomassen and Fjaera, 1996). Similarly, in juveniles of rainbow trout, increasing the number of meals inconsiderately (up to 32 meals a day) leads to poor growth performance (Linner and Brannas, 2001). As mentioned above, the frequency of feeding should not only take into account the transit rate of feedstuffs in the digestive tract but also give due consideration to the overall feed allocation per unit distribution. For instance, if the number of pellets delivered at a meal is far less than the number of fish in the tank or cage, this naturally leads to some fish not being able to have access to feed, leading to differences in growth within the batch.

6.3 Time of feeding

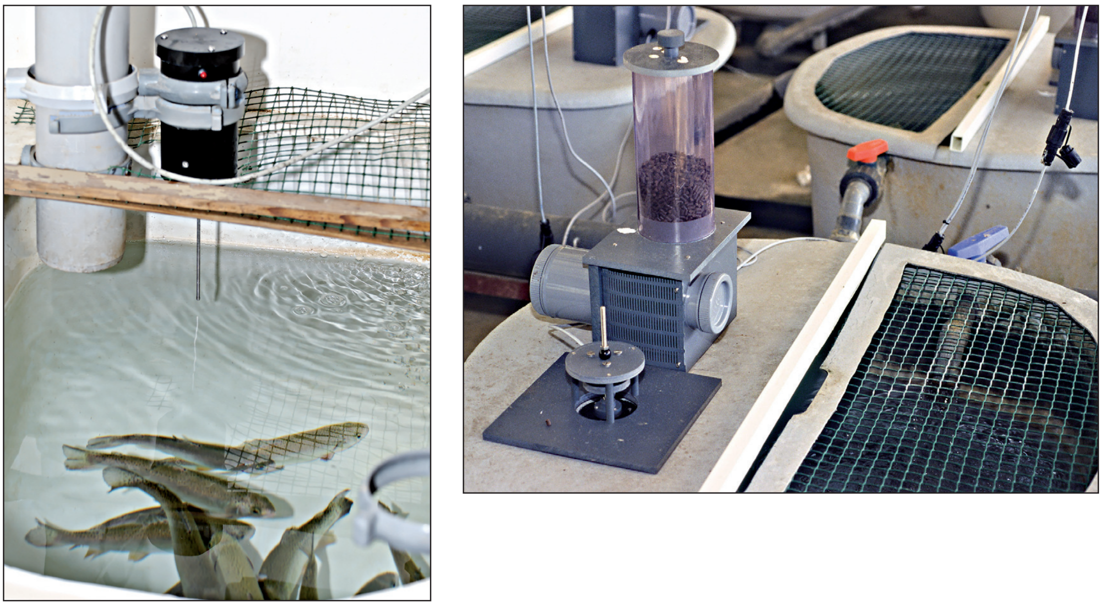
Since each species can have an endogenous feeding rhythm controlled by the central nervous system and the entraining endocrine factors and governed by environmental cues (especially photoperiod), much work has been undertaken to understand the feeding rhythms in farmed fish (Boujard, 1999; Madrid, Boujard and Sanchez-Vazquez, 2001). Even the timing of a single meal can influence feed intake, growth and nutrient utilization. For example, Boujard, Gelineau and Corraze (1995) found that compared to feeding at dawn, feeding totally out of phase with the endogenous rhythms of rainbow trout (i.e. at other hours of the day or at midnight) led to poor feed intake and lower protein or energy utilization. More recently, Noble *et al.* (2007d) evaluated the effects of different self-feeding regimes on performance and welfare of rainbow trout by feeding them either (i) a single meal at dawn of three hours duration; or (ii) three meals at dawn, midday and dusk of two hours duration each; or (iii) by giving continuous access to feed over a 12 hour period during the day. These authors did not find any significant differences in ration size, growth rate, condition factor, size heterogeneity, food wastage or feed efficiency between the different groups, although the levels of aggression (as evidenced by increased fin erosion) were highest in trout fed only a single meal, Similar data have also been obtained with Atlantic salmon (Noble *et al.,* 2007b, c).

6.4 Circadian rhythms of feeding

Using computer-controlled ‘eater meter’ devices specifically developed for the purpose of analyzing feeding rhythms, feeding activities and food preferences (Boujard *et al.,* 1992; Blyth, Purser and Russell 1993; Figure 14), circadian rhythms of feeding have been analyzed in several species with different ecological niches and feeding behaviours (e.g. cyprinids, salmonids, cichlids, silurids) under controlled conditions with free access to food (Boujard, 1999). All studied species showed rhythmic patterns of feeding activity, with diurnal or nocturnal peak activity (acrophase). Some species, e.g. European sea bass and common carp (*Cyprinus carpio*), are able to phase shift their rhythm of feeding from nocturnal to diurnal

FIGURE 14

Eater-meter device used for experimental studies for monitoring feeding behaviour, feeding rhythms and feed preferences in fish



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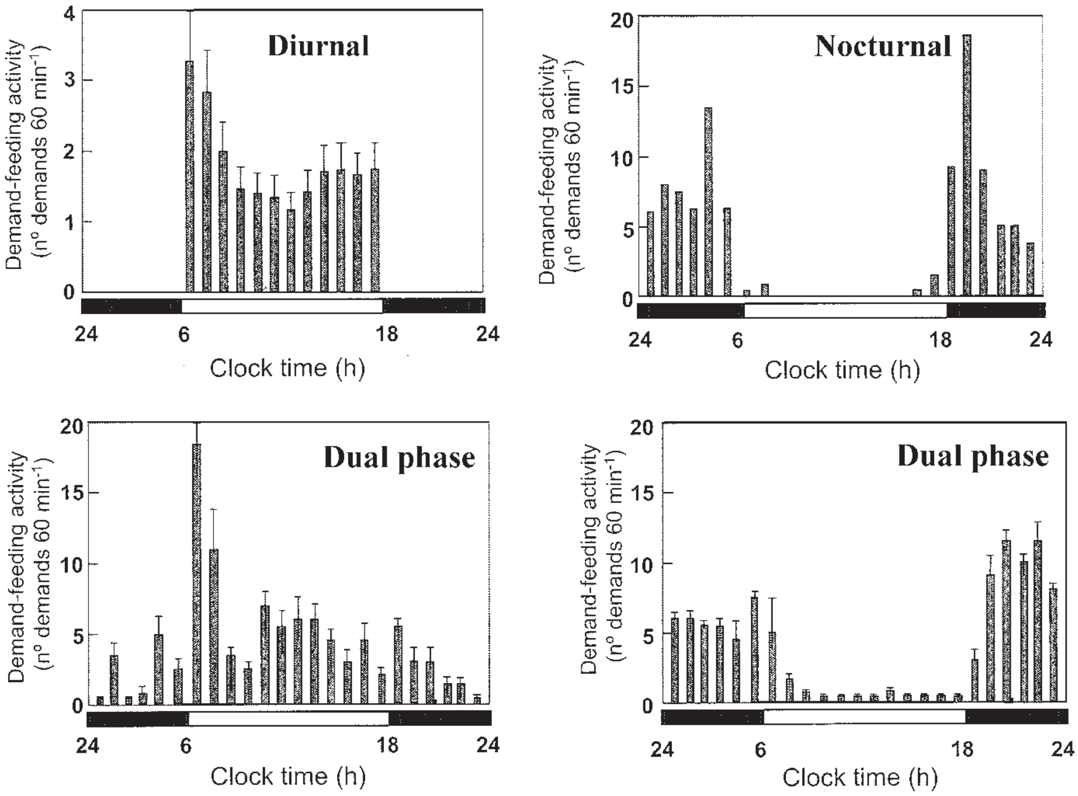
and *vice-versa*, showing some plasticity in behaviour and adaptation to changing conditions (Madrid, Boujard and Sanchez-Vazquez, 2001; Figure 15). Feeding activities are sometimes linked to endocrinological parameters and sometimes dissociated, and our understanding of the exact cues, environmental or otherwise, governing such rhythms are far from clear.

FIGURE 15
Patterns of demand-feeding activity exhibited by different species of fish



Source: Redrawn from Madrid, Boujard and Sanchez-Vazquez (2001).

6.5 Physiological mechanisms underlying feed intake

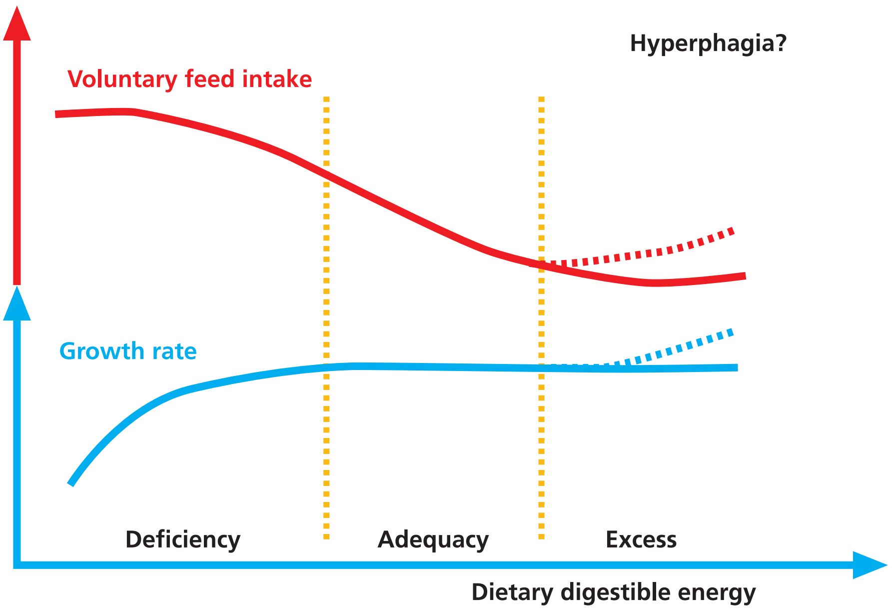
Within a given species, voluntary feed intake (VFI) will also vary depending upon the physiological status (e.g. during gametogenesis). It is well established that feed intake per unit body weight decreases with increasing body weight and increases with increasing water temperature within the thermal preferendum zone of a given species. Under stressful conditions such as hypoxia or high ambient ammonia levels, the VFI is also reduced.

The central role of the brain and the integrative or feed-back mechanisms involved in feed intake regulation has been stressed in most farm animals (Forbes, 1986). In fish, the exact involvement of the central nervous system in the control of appetite, satiety and feeding activity is only slowly being discerned. It is in fact even difficult to discern the notions of appetite or hunger in fish as with terrestrial animals. The role of the hypothalamus in the control of appetite and satiety, although established, implies a number of factors which can be divided into two categories, orexigenic (those which stimulate feeding) and anorexigenic (those which inhibit feeding). The involvement of neuropeptides such as Neuropeptide Y (NPY), orexins, galanin, agouti-related protein (AgRP), ghrelin, cholecystokinin (CCK), cocaine amphetamine-regulated transcript (CART), and corticotropin-releasing factor (CRF) are now being recognized as having similar orexigenic or anorexigenic actions in fish as in other animals (Nakazato *et al.*, 2001; Volkoff *et al.*, 2005). There are also indications that leptin might play a role in feed intake and energy homeostasis in the arctic char, as suggested by Froiland *et al.* (2010).

Our knowledge of the physiological control of feed intake of fish under farming conditions is mainly concerned with some environmental and biotic factors and to a lesser extent with a few dietary and nutritional factors. As regards nutritional factors, the prevailing idea that fish, like other animals, eat to satisfy their energy requirements, provided the feeds are adequate in all nutrients (Kaushik, Luquet and Blanc, 1981; Cho and Kaushik, 1990; Bendiksen, Jobling and Arnesen, 2002) remains valid. Even in their very early studies, Rozin and Mayer (1961) found that goldfish increase their food intake significantly in response to dilution of their normal diet with kaolin, appearing thus to eat for energy or nutrient value. Similar findings were also noted for European seabass fed diets supplemented with bulk agents (Dias *et al.*, 1998).

However, whether or not rainbow trout and salmon are subject to hyperphagia due to feeds with high fat and consequently high DE content remains a question of practical interest (Figure 16). While most data indicate that digestible energy is the factor limiting voluntary feed intake, there are also suggestions that other factors such as protein content, amino acid profile, orosensorial agents or post-absorptive metabolic control play significant roles. Based on what is known in terrestrial animals, two main theories behind appetite regulation – the 'glucostat' and the 'lipostat' mechanisms, both involving a central role of the hypothalamus, have also been analysed to a small extent.

FIGURE 16
Schematic relation between dietary energy supply and growth or feed intake



Source: Unpublished data of S.J. Kaushik.

The 'glucostat' theory implies the involvement of whole body glucose mass and the receptivity of the hypothalamus to such signals as regulating feed intake and appetite over the short term. In fish, data available today are very contradictory. In fact, under conditions of fasting as seen in migrating salmon, plasma glucose levels are higher than in fed fish (Sheridan and Mommsen, 1991). This is also seen in rainbow trout with high plasma glucose levels when fed feeds with low protein levels (Kirchner, Kaushik and Panserat, 2003). It appears then that the glucostat control of VFI is not operating in fish and if at all, it has little impact on feed intake over long periods.

The 'lipostatic' control is recognized as having a cumulative effect over time, affecting VFI over long periods and can thus have an effect on body mass gain. The accumulation of fat with increasing body mass can send satiety signals (leptins or other hormones) that suppress the feeling of hunger and thus reduce feed intake and maintain body mass. Whether such a mechanism operates in fish has been the object of a few studies. There is some evidence in fish that large fat stores reduce VFI over the long term (Jobling and Miglavs, 1993; Silverstein *et al.*, 1999; Ogata & Shearer, 2000; Regost *et al.*, 2001, Jobling *et al.*, 2002; Bendiksen, Jobling and Arnesen, 2002; Johansen, Ekli and Jobling, 2002; Johansen, Sveier and Jobling, 2003; Shearer, Silverstein and Plisetskaya, 1997).

Bendiksen, Jobling and Arnesen (2002) observed that Atlantic salmon parr compensated for differences in feed energy densities to maintain energy and nutrient intakes, and that lipostatic factors may be operating to regulate feed intake and growth.

Based on such ideas, attempts have also been made to tailor salmon body composition by diets varying in digestible protein to digestible energy ratios ranging from 16 to 26 g/MJ and by phase feeding the different diets over long periods. Morris *et al.* (2003) found that the confounding effects of season- and size-related increases in inter-individual variability made it difficult to tailor the yield or body composition of Atlantic salmon simply by conservative changes in the gross composition of the feeds.

Jobling and Johansen (1999) hypothesized that since there is an increased fat deposition in fish undergoing a period of nutritional restriction and subsequent catch-up growth when feed supply is restored, there might also be a lipostatic control of feed intake in salmonids. Subsequent studies by Johansen, Ekli and Jobling (2002) and Johansen, Sveier and Jobling (2003) were undertaken to test whether the lipostatic control of feed intake operates in juvenile Atlantic salmon, first by manipulating body fat content through feeds with low or high fat levels and then by challenging the lean and fat fish with the high- and low-fat feeds simultaneously. After an initial period of adaptation, body compositions converged among treatments and differences in feed intake reduced, providing some evidence for a lipostatic regulation of feed intake.

Subsequent studies by Geurden *et al.* (2006) undertaken with rainbow trout fed one of three diets having variable protein and fat levels showed that, under self-feeding conditions, fish of similar body mass had similar VFI without apparent compensation in terms of overall energy intake. Rainbow trout fed the high-fat diets had high body fat deposition but similar protein growth. The absence of any change in VFI in trout fed the high-fat diet suggests a low negative feedback by fat intake or by body fat content. Based on their observations of similarities in lean body growth, these authors favoured the idea that growing trout would regulate their VFI in order to meet the demand for maximal protein growth rather than to satisfy a predetermined energy requirement. Such concepts need to be verified in detail in fish generally confronted with feeds of varying nutrient content under farming conditions.

7. LESSONS LEARNT FROM SALMONIDS: APPLICATION TO TROPICAL AQUACULTURE

Tropical finfish farming has been growing at a relatively high rate. For instance, the production of tilapias has been increasing by about 10 percent per annum and that of milkfish by 4 to 5 percent (FAO, 2012). Production of other species such as the Indian major carps - catla (*Catla catla*), rohu (*Labeo rohita*) and mrigal (*Cirrhinus cirrhosus*) - has also been increasing. Although there are indications that the farming of these species is undergoing increased intensification, it is as yet difficult to estimate the exact amount of compound complete feeds that are being used for species such as the Chinese and Indian major carps, tilapias, milkfish, mullets and groupers.

7.1 Nutrient requirements

Of all the species mentioned above, data on nutrient requirements for all the essential nutrients are available only for common carp (Takeuchi, Satoh and Kiron, 2002), tilapias (Shiau, 2002) and, to a certain extent, for barramundi (*Lates calcarifer*) (Boonyaratpalin and Williams, 2002), milkfish (Lim, 1991; Borlongan and Coloso, 1993) and Indian major carps (Murthy, 2002). For other species, even those grown in large amounts (e.g. catfish in Viet Nam, major carps in the Indian subcontinent), nutrient requirement data are very limited. For instance, a commonly used essential amino acid (EAA) requirement profile for these fish is the one proposed by Ogino (1980) for carp and trout. This profile is also used for evaluating the essential amino acid content for a score of ingredients, as was done by Tacon, Metian and Hasan (2009). As far as essential amino acids are concerned, this in itself is not of serious concern, since there is a high degree of homogeneity between the amino acid profiles and requirements of different species (Cowey, 1994; Mambrini and Kaushik, 1995; Wilson, 2002; Kaushik and Seiliez, 2010).

The amino acid profile proposed by Ogino (1980) is based on the principle that since the main purpose of dietary protein/amino acid supply is to increase whole body protein accretion, one can calculate the requirements based on daily increments in the whole body protein-bound amino acids. It then appears that the ideal protein would be the one which reflects the whole body IAA profile of the corresponding species. The whole body protein-bound amino acid profiles are very similar among different species of teleosts or crustaceans (Table 8), and the amino acids deposited during growth can hence be considered to be similar. However, for essential fatty acids and micronutrients, data are sparse (Sargent, Tocher and Bell 2002; Kaushik, 2004), whereas these nutrients play a major role in growth as well as in maintaining the health and physiological well-being of fish. It is clear that the generation of a solid nutrient requirement database for all species of interest is essential.

TABLE 8

Whole body amino acid composition of different finfish and crustaceans (expressed as g/16 g N)

Amino acid	Finfish	Shrimp
Alanine	6.17 ± 0.82	4.86 ± 0.56
Arginine	6.16 ± 0.98	6.59 ± 1.20
Aspartic acid	9.19 ± 0.85	8.37 ± 0.34
Cystine	0.96 ± 0.26	0.78 ± 0.11
Glutamic acid	14.29 ± 2.49	12.55 ± 1.20
Glycine	6.81 ± 1.69	5.03 ± 1.32
Histidine	2.47 ± 0.63	1.85 ± 0.17
Isoleucine	4.29 ± 0.92	3.56 ± 0.32
Leucine	7.20 ± 0.70	6.13 ± 0.47
Lysine	7.38 ± 0.89	6.42 ± 0.51
Methionine	2.75 ± 0.45	2.18 ± 0.17
Phenylalanine	4.10 ± 0.47	3.44 ± 0.27
Proline	4.37 ± 1.13	3.13 ± 0.39
Serine	4.15 ± 0.47	3.27 ± 0.29
Threonine	4.39 ± 0.54	3.18 ± 0.14
Tryptophan	1.01 ± 0.29	0.90 ± 0.19
Tyrosine	3.02 ± 0.62	3.30 ± 0.40
Valine	4.73 ± 0.53	3.95 ± 0.61

Source: Kaushik and Seiliez (2010).

7.2 Use of formulated feeds

As mentioned above, we also do not have a clear idea of how much formulated complete feed is being used in tropical fish farming, despite attempts such as those by Tacon, Metian and Hasan (2009). There is a wide variety of studies showing that the correct use of adequately formulated feeds leads to improved net returns in terms of nutrients (e.g. nitrogen, phosphorus) as well as to economic benefits as compared to extensive or semi-intensive farming practices using mixtures of ingredients that are generally termed 'farm-made aquafeeds'. In almost all tropical finfish studied so far, there are clear indications that the use of formulated pelleted feed leads to better economic returns. By using balanced supplementary feed in conjunction with correct management of pond productivity, Tripathi *et al.* (2000) could achieve a production of more than 12 tonnes of Indian major carps per hectare. The benefits of using pelleted complete feeds for growing rohu in unfertilized ponds have been demonstrated (Anand, Manomaitis and Ramesh, 2006). Even very early studies with milkfish have shown that supplemental feeding can improve production and economic returns (Sumagaysay, Marquez and Chiu-Chern, 1991). Increase in tilapia production is also undoubtedly due to the use of complete feeds. The advantages of feeding groupers with formulated complete dry feeds have also been demonstrated (Bombeo-Tuburan *et al.*, 2001; Sim *et al.*, 2005; Rachmansyah, Palinggi and Williams, 2009). Studies on the feeding habits of mullets and the development of artificial feeds have been conducted for many years (Vallet *et al.*, 1970; Albertine-Berhaut, 1973), and there is continuing interest in developing feeds using plant ingredients, algae or yeast (Wassef, El Masry and Mikhail, 2001; Luzzana *et al.*, 2005).

One major constraint to adopting formulated feeds is that these feeds should be formulated using basic nutritional principles, meeting the requirements of the target species, and taking into account the specific farming systems. Given that a number of species of mullet and grouper are farmed, our knowledge on the nutritional requirements of these species is very limited. Since Kaushik (1998) proposed that the bioenergetic principles initially developed and applied to salmonids are applicable also to non-salmonids, such an approach has been applied with success for gaining insight on protein and energy requirements and for formulating feeds for groupers (Lupatsch, Kissil and Sklan, 2003; Lupatsch and Kissil, 2005) and barramundi (Glencross, 2006). Given the issues of the availability and cost of fishmeal and fish oil at the global level, the achievements made with salmonids can be easily extended to these species.

7.3 Feed form and quality

In terms of feed quality, the relative advantages of using dry feeds as compared to trash fish or moist feeds are as valid for tropical species as for salmonids. While it is still common to use mixtures of ingredients (e.g. cereal bran + oil cakes), the use of pelleted feeds is becoming more common, and the same constraints regarding the nutritional and physical characteristics of feeds apply.

It has often been considered that dry diets are inadequate to feed small fish larvae during the first stages of feeding, and that such diets could be used successfully only after the larvae had been fed on live food for some time ('weaning'). However, after more than 20 years of research, considerable progress has been made in the development of starter feeds and a feeding system for first-feeding cyprinid larvae (Charlon and Bergot, 1984; Charlon *et al.*, 1986). Since then, this possibility has been demonstrated in a number of species, including European seabass (Cahu *et al.*, 1998). The development of nutritionally complete feeds having feed particle size corresponding to the size of the larvae (Table 9) or the diameter of the buccal opening and an efficient way of feed distribution in a more or less continuous manner (Figure 17) can be applied right from first-feeding onwards to grow the larvae of many fish. Besides the system as presented by Charlon and Bergot (1984), belt-feeders can be used to grow these larvae with formulated complete feeds. Indeed such studies have even led to the development of semi-purified diets for first-feeding larvae and to the evaluation of the nutrient requirements of first-feeding larvae of carp (Gouillou-Coustans, Bergot and Kaushik, 1998) and European seabass (Mazurais *et al.*, 2008). Similar progress can be made with many of the tropical species. Another major advantage is that of producing good-quality fry or juveniles for on-growing in the farms.

TABLE 9
Species of fish in which larvae have been shown to grow well using solely inert dry formulated complete feeds from first-feeding onwards

Species	Temperature (°C)	Size at first meal (mm)	Dry feed intake
Grayling, *Thymallus thymallus*	8–12	10–12.5	yes
Siberian sturgeon, *Acipenser baeri baeri*	17–20	11–13	yes
European whitefish, *Coregonus laveratus*	12–14	10–12	yes
Allis shad, *Alosa alosa*	10–22	10–11	yes
Wels catfish, *Silurus glanis*	24	9–10	yes
North African catfish, *Clarias gariepinus*	25–28	7	yes
Common carp, *Cyprinus carpio*	24	6–7	yes
Goldfish, *Carassius auratus*	24	5.5–6.5	yes
Pike-perch, *Sander lucioperca*	17–18	5–6	yes
European seabass, *Dicentrarchus labrax*	15–20	3–4	yes
Gilthead seabream, *Sparus aurata*	20–22	3	yes

Source: Unpublished data of S.J. Kaushik.

FIGURE 17
Automatic feed dispenser developed for rearing larvae with dry feeds right from first-feeding

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Switching from traditional feeds to formulated feeds also requires adequate feeding and feed management practices that take into account the endogenous feeding rhythms of the species concerned. Changes in patterns of feed intake as observed in salmonids are also seen in other species, each of them showing distinct patterns (Talbot, Corneillie and Korsoeen, 1999). In stinging catfish (*Heteropneustes fossilis*), Sundararaj, Nath and Halberg (1982) showed that both feed intake and weight gain are maximal during the daily dark phase. In tilapia grown under laboratory conditions, the locomotor activity is diurnal whereas the feeding activity appears to be nocturnal (Fortes-Silva *et al.*, 2010). Under self-feeding conditions, many species of fish also appear to have reduced stress (Endo *et al.*, 2002).

7.4 Feeding systems

Under pond-culture conditions, or even in cages, it is difficult to control feeding to satiety for all fish when hand-feeding is used. Feeding fish some given proportion of body mass is also subject to error, given that the construction of such tables has little scientific basis. Full recognition of the endogenous feeding patterns, and taking complete advantage of such biological rhythms, can be used to control feed intake more effectively and to avoid feed wastage, a major concern in terms of economics and environmental quality. Feeding strategies should also aim at minimizing competition for feed within a group and thus arrive at homogenous group performance.

Simple self-feeding (demand) systems based on bamboo poles with feed-bags are already being used in the pond-culture of Indian major carps, for example (Figure 18). Sophisticated techniques using hydrophone sensor-based feeding systems have also been developed to control feed intake in pond aquaculture (Figure 19). It is also becoming increasingly evident that using feeds with the right buoyancy properties (i.e. floating feeds) can be an excellent tool in feed management, in as much as the feed distribution can be monitored (Figure 20). Such extruded floating feeds, although not containing lipid levels as high as those used for salmonids, can improve starch digestibility and reduce fines and possibly some anti-nutritional factors. In the absence of such self-feeding systems, application of bioenergetic principles should become standard practice to derive feeding charts based on the nutritional value of feeds and the requirements of the species under specific farming conditions. This will address and possibly eliminate the major question: "are we feeding the fish or the ponds/cages?"

FIGURE 18
Simple demand-feeder (left);
Bamboo poles with feed-bags used as demand feeders in pond culture of major carps (right)

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FIGURE 19
Diagram and photo of hydrophone feeding control systems:
sensor-based feeding control for pond aquaculture

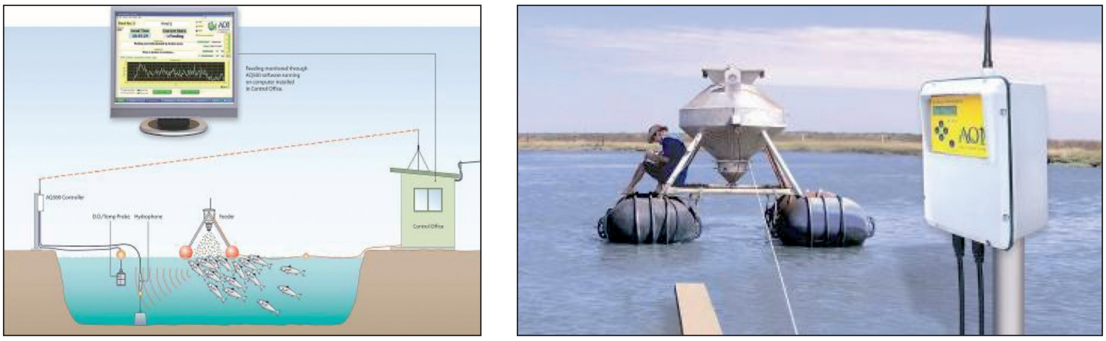

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FIGURE 20

Floating feeds can be a very useful management tool for controlling feed intake

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Notes: left: floating feeds used for Indian major carp reared in ponds; right: floating feeds for rearing Nile tilapia in a land-based farm in Egypt.

8. CONCLUSIONS

At a stage when much focus is given towards the sustainability of fish farming, especially with regard to the correct allocation of feed resources, feed-based aquaculture is receiving increased public attention. Bioeconomic analyses are in favour of fish farming based on strong scientific evidence and applied nutrition for sustainable aquaculture development. In this context, correct feeding strategies are indispensable, and the experience gained with salmonids can well be applied to other species.

Feed distribution should ensure adequate nutrient supply to the whole group to achieve homogenous group performance. Good feed management practices should allow a reduction in feed/nutrient losses and reduced labour costs and/or manpower. Feeding strategies should be adapted to the biological rhythms of the target species. Feeding tables should be developed on a scientific basis, in order to meet the nutrient/energy requirements for specific production characteristics.

Much progress has been made in salmonids in the development of nutritionally adequate feeds, as well as in the physical characteristics of feeds through improved feed manufacturing processes. Progress made in improving feed and nutrient utilization efficiencies has also been supported by improvements and specific methods of feed delivery that avoid feed wastes, thus reducing environmental impacts. There is also clear evidence from comparative studies that similar progress can be achieved with other finfish species; indeed, such methods are already being practiced, for instance, in the Mediterranean area for the farming of European seabass and gilthead seabream. The principles behind these methods and the practical approach adopted by the feed industry and the farmers are very much applicable to tropical aquaculture conditions, where similar pressures exist with regard to improving feed efficiency and reducing financial and environmental burdens.

Despite the progress made in salmon and trout farming, even in salmonids it is still felt that more standardized test methods and automatic feeding systems are required by the farming industry. Lack of control of feeding can have adverse effects on the environment, increase costs for the farmer and lead to other effects, such as attracting wild fish from the neighbouring environment. All efforts should be made to avoid feed and associated nutrient losses into the environment. Under cage-culture conditions, feeds should be highly digestible and feed distribution adequate to obtain homogenous group growth performance, and the resulting faeces should not accumulate under the cages. In land-based farming systems, the faeces produced should be decantable and easily collected in order that they are not released into the natural waters.

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