AN AQUACULTURE
TECHNICAL BRIEF

Optimal Feed and Feeding Management for Sustainable Aquaculture

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A PUBLICATION OF THE UNIVERSITY OF WISCONSIN-MILWAUKEE SCHOOL OF FRESHWATER SCIENCES AND UNIVERSITY OF WISCONSIN SEA GRANT INSTITUTE

October 2021

OPTIMAL FEED AND FEEDING MANAGEMENT FOR SUSTAINABLE AQUACULTURE

INTRODUCTION

Why We Care About Feed

In the practice of aquaculture (raising fish) or aquaponics (raising fish and plants), we know that what we feed and how we feed the fish are vitally important to fish health — and in turn, to the quality and profitability of the fish harvest. However, there is little detailed information available about aquaponics feed because it is still a young area of research. There is some information available, such as how to calculate roughly how many grams of feed to use based on how much produce you are growing, but this is only an approximate estimation. To achieve aquaculture success, every system requires a fine level of detail beyond such estimations.

While more specific guidelines have yet to be researched and developed, the information provided in this technical brief covers the basic principles of feed (what to feed) and feeding management (how to feed) in aquaculture and aquaponics. It provides a practical starting point for practitioners to begin their feed and feeding management.

Why do we care about feed? The primary objective of feeding is to get the right type and amount of nutrients to the fish and the plants, so that they are healthy and productive. A second objective is to minimize waste, which incurs work and expense in its removal and can impact the health of the system. A third objective is to reduce unnecessary costs to increase your profit. Finally, a fourth objective is to feed your fish and plants to gain the specific qualities required to suit marketplace preference.

How can we meet these objectives? There are two variables to consider for both the fish and the plants: feed selection (what to feed) and feed management, which includes how much to feed and the most efficient method for feeding.

Feed selection and feed management affect many aspects of your harvest. Proper feed is necessary for good production because different fish require different nutrients and have different feeding behavior. Without a proper feed management plan, dietary nutrients will not be delivered efficiently to your fish. In addition, the end product quality is highly dependent on feed quality and the method by which fish are fed.

For example, different feed can affect sensory attributes such as the color, flavor and texture of the end product. Figure 1 illustrates a sensory test that measures shrimp attributes after they were fed diets replacing fishmeal with duckweed protein, which was shown to increase the firmness of shrimp muscle. Similarly, figure 2 shows the color of cooked shrimp varies due to different levels of astaxanthin supplemented in feed either from microalgae or a synthetic form of astaxanthin (Ju et al., 2012). In both cases, while the taste may be the same, the difference in texture and appearance is quite noticeable.

Desirable attributes are different for each species, and market preferences are varied even for the same product. For example, very fatty, juicy or soft fish is not desirable for certain species of fish in the marketplace. But other fish, such as salmon, may need to have sufficient fat to make good sashimi. Some practitioners will change feed management, such as restricting feeding or changing to different feed, to change the firmness, color or flavor of fish fillets before the fish are harvested for market. This type of diet change does not necessarily affect the growth or quality of the product, only the general presentation, which in turn can affect the market price.

Feed selection and feed management are also important considerations for water quality management. Figure 3 illustrates the effect on water quality by comparing feeding fish with diets based on plant protein or fishmeal protein. The plant-based feed led to increased waste particles in smaller size compared to the fishmeal-based diet. This suggests that the culture systems will need to be managed differently in order to maintain the same water quality, which will affect costs of running the system.

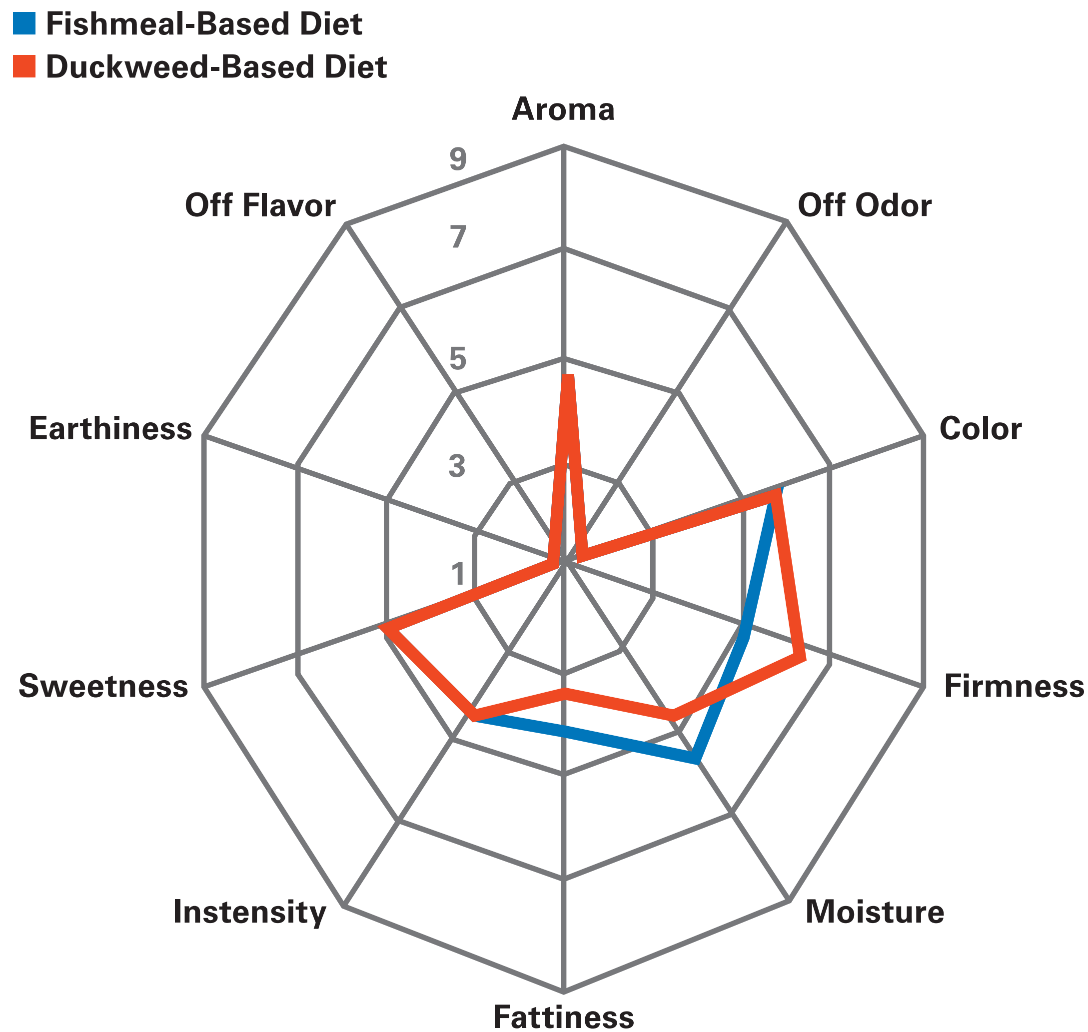

Fig. 1. Comparison of sensory attributes for shrimp fed a diet substituting fishmeal with duckweed protein concentrate. (D. Deng, 2016.)

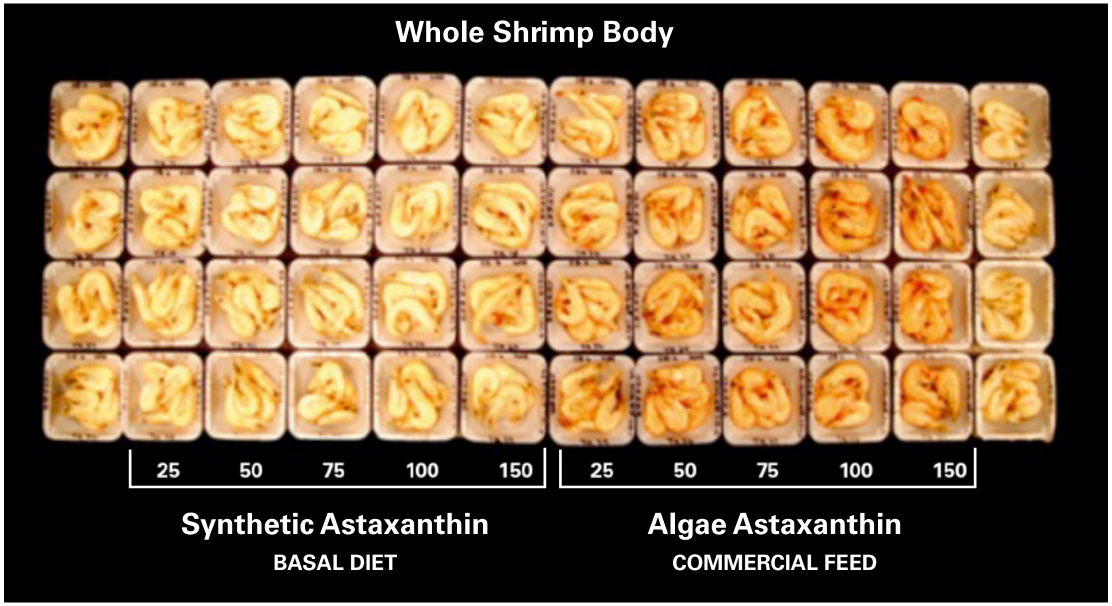

Fig. 2. Color of cooked shrimp affected by feed supplemented with different levels and sources of astaxanthin. (Z-Y Ju et al., 2012.)

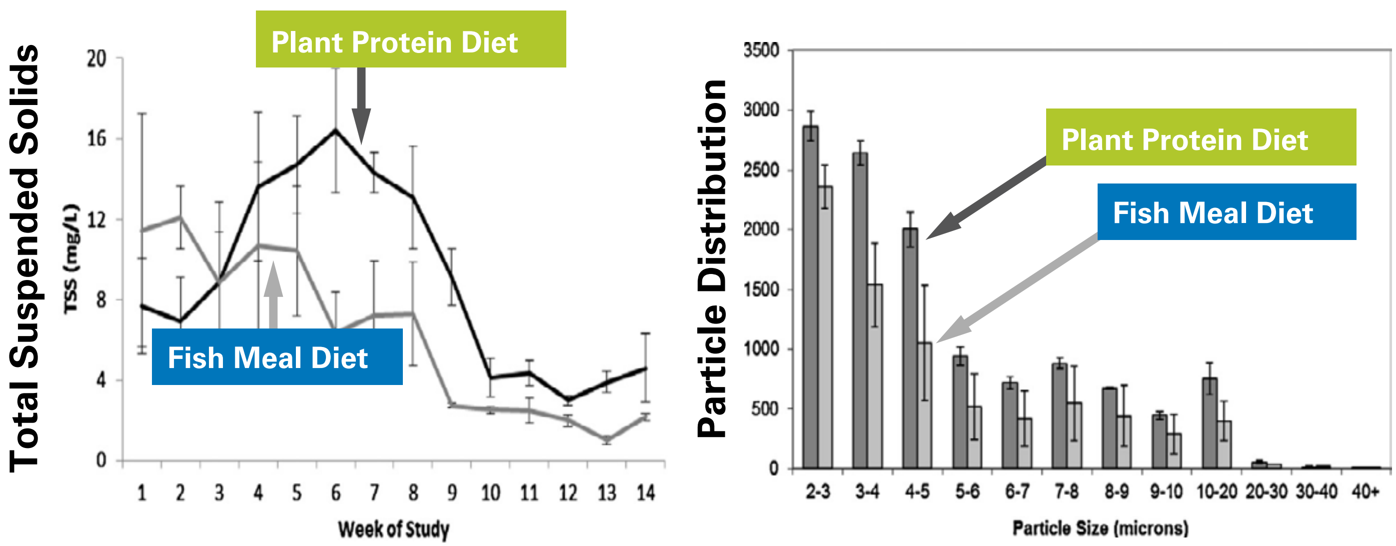

Fig. 3. Effect of different feed on water quality management. (J. Davidson et al., 2012.)

FEED NUTRITION FOR SPECIES, LIFE STAGE AND CULTURE CONDITIONS

How do we select the right feed for the fish? There are three primary considerations in choosing the correct feed: the species, its life stage and the culture conditions in which they are being raised.

First, you must consider the species you are raising. There are more than 300 species of cultured fish. The most common aquaculture species include carp, tilapia and other cichlids, catfish, Atlantic salmon, white leg shrimp, and mollusks such as clams and oysters. Each of these require different nutrition. For information regarding feed and specific species, visit the National Research Council of the National Academies (NCR) at nationalacademies.org/topics/agriculture. In general, the nutritional composition of fish feed is protein (25-55%), carbohydrates (10-50%) and lipids (5-30%), with added moisture, vitamins and minerals. This composition is adjusted for different species and their stage of life as shown in figure 4.

Second, different life stages have different nutritional requirements and require different physical qualities of feed (i.e., pellet size, texture, color or density). When it comes to diet, stage of life is as important in fish as it is in humans; that is, larvae require special feed in terms of nutrients, shape and size, for the same reasons we give formula to our babies with a bottle. Larvae are underdeveloped upon hatching. They lack efficient feeding capacity and ability to digest and absorb exogenous nutrients, and they can only swim limited distances for feed/prey. They are in a physiological stage of fast growth with minimum nutrient storage capacity. Thus, providing larval fish with the nutrients they require, through exogenous

NUTRIENT REQUIREMENT OF DIFFERENT SPECIES

Species	Digestible energy (Kcal/kg)	Digestible protein (%)
Salmon	4200	40
Tilapia	3400	29
Carp	3200	32
Shrimp	300	30-34

NUTRIENT REQUIREMENT AT DIFFERENT LIFE STAGE

Species	Nutrient	LIFE STAGE		
		Fry	Juvenile	Grower
Salmon	Protein (%)	48-50	45	35
	Lipid (%)	18	15	33
Catfish	Protein (%)	50	35	28-32
	Lipid (%)	13	8	6

Fig. 4. Nutrient needs based on species and life stage. (R. Hardy et al., 2011.)

feeding, is a very challenging process for hatchery management. For the early life stage, the larvae of most species will require live feed, such as brine shrimp, rotifer or zooplankton because they are small enough for the larvae to eat and they will not leach critical nutrients the way formulated food of that size will. Nutrients leached from the formulated diet will jeopardize both nutritional quality of feeding and the water quality of the culture system. Due to limited formulated feed available, for most aquaculture fish species we rely on live feed, or a combination of live feed and artificial feed, to culture larval fish until they are trained to eat more economical formulated feed.

Figure 4 illustrates the difference in nutrient requirements for four species: salmon, tilapia, carp and shrimp (Hardy et al., 2011). Note that the protein level can range from 28 to 50 percent. Figure 4 also illustrates that for the same species of fish, the nutrient requirements vary depending on the life stage. The fry (larval fish) have a higher protein requirement than they will as adults.

The third consideration is which diet will optimize production efficiency within your particular cultural conditions. Some culture systems, such as a pond or an outdoor raceway, may need fewer nutrients from the feed because there is food available naturally (algae, zooplanthon, phytoplankton). For example, a study by Lovell (1989) showed that tilapia raised in a pond system can be fed a diet containing 26% protein, but fish raised in raceways will need a higher protein level (32%).

For a high-density tank system or a recirculating system, you may need to provide a diet containing a higher amount of digestible nutrients. This will allow fish to get enough nutrients while creating less waste in the system. Less waste makes management of water quality easier.

Furthermore, in aquaponics we often need to supplement the system with iron, calcium, potassium or other minerals to optimize plant production. Some practitioners use nitrogen or protein from fish feed as a nitrogen source for the plants. However, it should be noted that protein from fish feed is an expensive source of nitrogen to be used as a plant fertilizer. It is important to do an economic analysis to see if the expense of fish feed is economically viable in an aquaponic system. The inputs you use for plant fertilizer depend on your production plan and source of profit (i.e., fish or plants or both). If your intention is to grow and sell produce, then use a less expensive plant fertilizer. But if your intention is to grow and sell fish, you still need to care about the quality of the feed and how much you need to raise healthy fish.

CHOOSING THE PHYSICAL CHARACTERISTICS OF FEED

When we consider feed selection, the feeding habit or behavior of the species is another important factor; that is, whether they are detritus feeders, herbivores, omnivores or carnivores. Each habit needs a different nutrient composition. For example, carnivorous fish generally need a diet containing a higher level of protein and lipid than herbivores or omnivorous fish, which can handle more carbohydrate in their feed.

FOR A HIGH-DENSITY TANK SYSTEM OR A RECIRCULATING SYSTEM, YOU MAY NEED TO PROVIDE A DIET CONTAINING A HIGHER AMOUNT OF DIGESTIBLE NUTRIENTS.

Following are descriptions of fish feeding habits:

- **Detritus feeders** consume decomposing plant and animal parts. Examples are sea cucumber, crab and mud carp.
- **Herbivores** consume plant materials. Examples are grass carp, silver carp, milkfish and rabbitfish.
- **Omnivores** consume both animal and plant foods. Examples are common carp, catfish and tilapia.
- **Carnivores** consume a meat-based diet. Examples include salmon, trout, sturgeon, sea bass and black carp.

Additionally, we must understand the feeding mechanism or physiology of each species. Some fish, like sturgeon, are scavengers that nibble constantly and prefer sinking pellets. For this fish we should either provide them feed pellets with high water stability or we should increase feeding frequency. Salmon and tilapia, however, are meal feeder fish that grab things and swallow them. Therefore, they either can be fed less frequently or with floating feed pellets. Pellet size and texture are important features because some fish chew and others do not. Some fish prefer a softer, semi-moist diet, and some prefer a harder, dry diet.

Following are descriptions of feeding mechanisms:

- **Bottom feeder/scavengers** feed well on or near the bottom of a body of water. Examples are flounder, eels, sturgeon and catfish.
- **Plankton filter feeders** strain suspended matter and filter out the undesirable parts. Examples are silver carp and paddlefish.
- **Macrophyte-eaters** prefer or selectively eat some species of macrophytes as part of their diet. Examples are grass carp and crayfish.
- **Predators** prey upon other fish or animals. Examples are salmon, grouper and sea bass.
- **Parasites** attach themselves to other fish and suck blood from the host fish. An example is lamprey.

Fish size is an important factor for determining feed pellet size. For example, if you feed large fish with small pellets, the fish will invest more energy in catching food than they will obtain from eating the food, causing malnutrition. In contrast, if the pellet is too large for the fish, the fish may not be able to catch it or digest it properly. Furthermore, that small feed particles leach out nutrients more quickly than large particles. Ideally, we should feed fish with the optimal size pellet so that they can easily eat and digest to get the nutrients they need.

It’s worthwhile to note that smaller feed pellets require specific processing, which requires more energy for manufacturing and therefore increases the feed price. As a cost-cutting measure, a common mistake in fish farming is to crumble large feed pellets to a smaller size for feeding fish in earlier life stages. This is not recommended, not only because fish need different nutrition in earlier life stages, but also because

Fig 5. Physical Characteristics of Aquatic Feeds.

- **Texture:** dry, semi-moist or moist feeds
- **Pellet size:** density and shape
- **Buoyancy**

DENSITY RANGE (G/L) OF FEED BUOYANCY	SEA WATER @20°C	FRESH WATER @20°C
Fast Sinking	>640	>600
Slow Sinking	580-600	540-560
Neutral	520-540	480-520
Floating	<480	<440

the crumbled pellets have decreased water stability and will leach nutrients easily.

Thus, when choosing feed, we must consider the correct nutritional composition, physical characteristic (texture, size, and buoyancy) for the breed and its life stage, as well as the breed's feeding habit and mechanism. Also consider the binding agent that holds the ingredients together to form a pellet. Wheat flour and corn flour are commonly used for this purpose and help to keep feed pellets water stable and reduce leaching of nutrients. Figure 5 illustrates several different physical characteristics of feed, as well as buoyancy density ranges for feed in sea water and fresh water.

TYPES OF FEED: LIVE FEED VERSUS FORMULATED FEED

There are significant advantages to using dry formulated feed as opposed to live feed. Formulated feed is easy to handle and store, and can be stored up to three months from its production date. Dry feed is reliably available, and the price is stable. With live feed, such as brine shrimp, retail availability and nutritional quality are not always stable. Factors such as light exposure, temperature and water salinity will influence its quality.

Biosecurity is another concern for using live feed, which is easily contaminated with bacteria or pathogens and may introduce disease into the production systems. In contrast to live feed, dry formulated feed is better controlled. During processing, such as the cooking extrusion method, feed is exposed to high temperatures and pressure treatments which kill bacteria and pathogens.

It is important to note the difference between feed ingredients and feed nutrients. Nutrients are what the fish need to grow, and ingredients are elements put into the food that deliver those nutrients. As an example, we can compare a soy-based diet to a fish-meal-based diet. Both diets deliver the nutrient of protein, but one ingredient is sourced from plants and the other from animals. The quality of nutrition provided by either protein source depends on the food formulation and digestibility of nutrients. If the feed is formulated correctly with all nutrients required by the targeted species and every nutrient is digestible and balanced, it doesn't matter to the fish if the protein is delivered through a soy ingredient or a fishmeal ingredient. In fact, some studies have shown that, depending on how they have been formulated and processed, plant-based diets are very effective in supporting growth. The same feed formulation can result in pellets that sink or float depending on their processing (cooking) method. Feed formulation and its nutritional quality will vary depending on ingredients used. For example, some plant ingredients may not have enough minerals and require added supplements to balance the nutrition required for a fish.

THE QUALITY OF NUTRITION PROVIDED BY EITHER PROTEIN SOURCE DEPENDS ON THE FOOD FORMULATION AND DIGESTIBILITY OF NUTRIENTS.

The objective of feed management is to provide the fish (aquaculture system) and plants (aquaponic system) with the appropriate diet, while containing input costs and pollutants. Therefore, when we consider feed management, we are planning:

- when to feed,
- how often to feed,
- how much to feed, and finally,
- the method which is the most advantageous and efficient.

While precise answers to these questions are still being researched for different species of fish, there are a few fundamentals we will review here.

FEEDING TIME, FREQUENCY AND RATE

When planning your feed management, start with the recommended feeding time, frequency and rate for your fish species. You can then fine-tune your procedure considering variables such as atmosphere of your lab (light and temperature), water quality, fish life stage and labor cost.

When Should Fish Be Fed?

Plan your feeding schedule based on recommendations from feed producers or other reliable resources. However, it is critical to check water quality (e.g., temperature and dissolved oxygen) before every feeding to avoid overfeeding. Overfeeding generates uneaten or undigested food which becomes waste in the form of nitrogen and ammonia that can be toxic to fish. As a general rule, it is better to underfeed your fish than to overfeed them. The fish won't be harmed if they don't eat for one day, but overfeeding could easily jeopardize water quality and kill them. However, a balance is critical, as you will lose production efficiency if underfeeding lasts for a longer period.

If there is a significant change in water temperature, stop feeding until the temperature is stabilized. Temperature shifts can affect the feeding behavior of the fish, which in turn could lead to overfeeding or underfeeding. For example, if tilapia are in water that is 72 degrees Fahrenheit (too cold for this fish), they will not eat at the same rate as when they are in the appropriate water temperature of 90 F. The fish in the 72 F water may only need 50 to 60% of what the fish in the 90 F water need because fish eat more in a higher water temperature. If you are following recommendations of a feed manufacturer, it is worthwhile investigating not only the amount of feed to give, but

AS THE FISH GROW, YOU WILL NEED TO DECREASE FEEDING FREQUENCY AND QUANTITY.

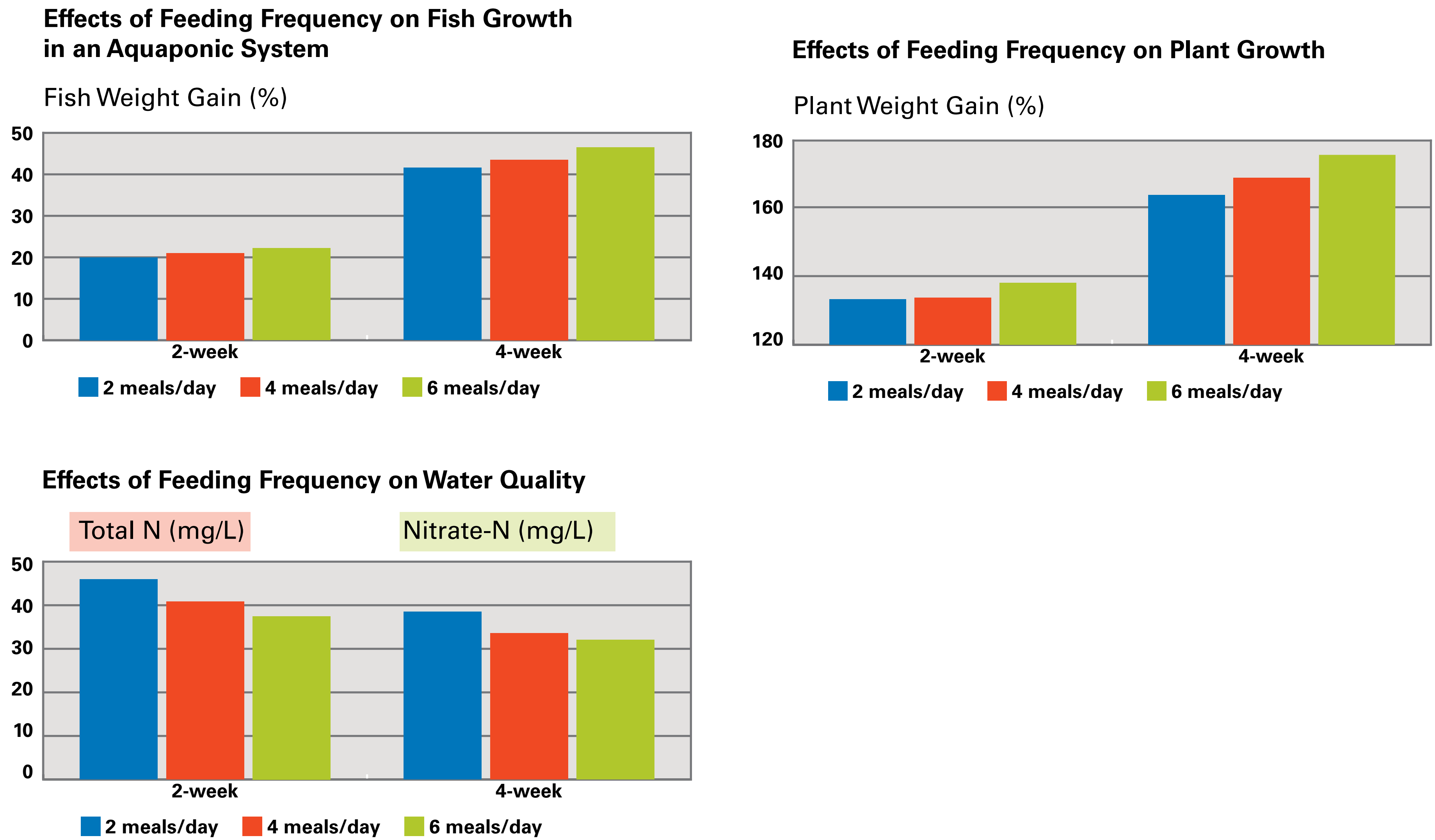

Fig. 6. Comparing effect of feeding frequency on fish and plant growth and water quality. (J-Y Liang & Y-H Chien, 2013.)

also optimal water temperature to avoid overfeeding, increased waste and decreased water quality.

The exception to the overfeeding rule is when the fish are in their early life stage. With larval fish, even if you feed them at a feeding rate of 100 percent based on their body weight, it may not be enough to support maximum growth, depending on the fish stock density, swimming capacity and tank size. In a recirculating aquaponic system, which is typically at a high stocking density, you will want to feed at a higher quantity and frequency. Otherwise, the aggressive, fast-moving fish will get the food and the slower ones will not have enough. As the fish grow, you will need to decrease feeding frequency and quantity.

How Often Should Fish Be Fed?

Optimal feeding frequency for aquaponic systems has yet to be fully researched with different species; however, there are some interesting data available.

Liang and Chen (2013) conducted a six-week study on aquaponic tilapia evaluating the effect of different feed frequencies on production of fish and plants, as well as water quality (figure 6). In the study, the same amount of feed is given daily and the daily feed ration is divided by the feeding frequency: two, four and six meals per day. Fish growth is maximized by the highest frequency feedings, suggesting that the fish absorb more nutrients with smaller, more frequent meals. When they are overfed, they absorb only the amount of nutrients they need at the time, and the rest may not be consumed or may pass through the digestive tract, creating more waste and therefore lower water quality. Similar optimization results are shown in the plant growth, as well as with the decrease of pollutants in the water.

While these data suggest higher feeding frequency will ultimately increase your profit, you must also consider associated expenses of increased wages paid to staff who do the feeding.

How Much Should Fish Be Fed?

It is important to understand the relationship between how much feed you give your fish and how much weight they gain. This relationship is known as the *feed conversion ratio*, or FCR.

To calculate the FCR, divide the weight of feed given by the total weight gain of fish. In general, the ideal FCR is a maximum of 1 to 2. If your FCR is higher than 2, then you need to adjust your feed management to improve the diet. If you can get 1 or lower, you are optimizing your investment in feed.

FEED CONVERSION RATIO
FEED FED ÷ FISH WEIGHT GAIN

Feeding is important not only for growth, but also for fish health and quality. You want to grow muscle (fillet) in the fish because that is what people buy. However, if you feed too much, the excess nutrients may create excessive viscera and fatty liver. These excess organs may constitute as much as 10-15% of the total fish weight and cannot be sold. The fish may not die from overeating, but poor fish health is likely, resulting in both lower-quality fish and a higher investment in feed.

Restriction (fixed) feeding and *satiation feeding* are two common tactics to manage feeding quantity. Restriction feeding is based on a predetermined feeding rate, which is defined as feed amount per 100 grams of fish. A feeding rate is determined based on estimated growth rate (how fast your fish grow during a period of time) and feed conversion ratio (how much feed is needed to produce a kilogram of fish) of a targeted species. The feeding rate is decreased with the increase of fish size (figure 7). You must periodically estimate the biomass in your system to determine a sound feeding rate. Satiation feeding is the simple practice of feeding the fish as much as they will consume (maximum feed intake) to achieve maximum growth. For this practice, it is critical to pay attention to feeding response in order to avoid feed wastes and maximize feed intake. For restriction feeding, it is necessary to monitor fish growth or fish weight to determine the correct feeding rate. This process is time consuming and stressful to the fish. Comparing to restriction feeding, the advantage of feeding to satiation is less handling of fish during weighing, which decreases stress.

For aquaponic systems, you can estimate how much feed is needed to feed your fish and satisfy the nitrogen requirement for your plants. For example, if the digestibility of protein is 90%, there will be 10% protein waste, which provides nitrogen to plant production. You will need to assess whether this total nitrogen is sufficient or too much for your vegetable production. However, the 90% digestibility of protein is not a fixed rule. Some protein may have digestibility of only 80 or 85%, but not as much as 90%. This will translate to more nitrogen waste from feed. Feed manufacturers can provide rough digestibility data, which can be used for your calculation. But this is only a starting point. If you overload the culture system by overfeeding the fish, adding more vegetables can remove the nitrogen waste being recirculated to the fish tanks.

FISH WEIGHT (G)	FEEDING RATE (% BODY WEIGHT)
1	11
5	6.5
15	4.6
30	3.6
60	3.0
100	2.5

Fig. 7. Feeding rate of cultured tilapia. Smaller fish require feed at a greater percentage of body weight per day than larger fish. (A. McGinty and J. Rakocy, 2005.)

FEEDING METHOD

Feeding method refers to hand feeding or automatic feeding. Each of these methods has pros and cons and is best determined by the size of the system and the scale of production. With hand feeding, there is the benefit of an increased opportunity to observe your fish and water quality. For large-scale farms, hand feeding may be too time intensive, requiring expensive levels of staffing, and there is higher risk of human error. An automatic mechanized feeder prevents human error and can save on labor expenses, but the initial investment in the equipment could be significant. Note that restricted or fixed feeding is recommended when automatic feeders are used.

FEED STORAGE

You will invest significant resources into feed; therefore, it is important to protect that investment with sound purchasing and inventory practices. You must buy the right amount of inventory so that you can attain savings on bulk purchases, but not so much that the feed cannot be stored in your space or used within three months from the production date (not the buying date).

When it comes to freshness of food, once again, we can compare fish to humans; we prefer fresh food because it tastes best and is most nutritious. It is important to have a full inventory turnover of fish feed every three months because it contains significant amounts of lipids, vitamins and minerals that are all vulnerable to oxidation. Refrigerating food may extend the shelf life, but there will be the added expense of the energy to power the refrigeration, and the feed can still go bad if it oxidizes before being moved to cold storage.

Humidity can also diminish the quality of your feed. The storage space must be cool and well ventilated to keep humidity at 70% or lower. Stacking feed bags too high not only decreases ventilation for the lower bags but may also require more handling, which can cause accidental damage. If the feed packaging is damaged, it can ruin the feed by exposure to moisture and oxidation. Additionally, the smell of fresh food emitted from a damaged package can attract pests. Therefore, sound purchasing and inventory practices not only protect your initial investment in the feed, they also decrease added costs of electricity and pest control, while keeping your fish healthy.

CONCLUSION

In this technical brief, we have discussed critical factors related to feed selection and feeding management, which are determined by the fish species, life stages and feeding behavior, and specific culture conditions. The information discussed here is mainly based on aquaculture research (raising fish). We still know very little about feed nutrition and feed management for aquaponics (raising fish and plants together).

For most aquaculture species, we do not yet have a full understanding of their nutrient requirements. Feed is formulated mainly based on the study of a few species, such as Atlantic salmon, common carp, tilapia, catfish, rainbow trout and white leg shrimp. The same feed may not be optimal for a new species. Therefore, we still need to research these information gaps in order to support the growth of the aquaculture industry.

While nutrition is an important consideration in feed planning, optimal feeding management has a significant impact on production cost and culture environment. Without a doubt, feed cost and overall impact on environment are critical factors when considering management of feed and feeding.

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Credits: Bonnie Halvorsen, writer; Elizabeth White, editor; Yael Gen, design.