

Smarter Feeding in Aquaculture: Advancing Precision Feeding and Better Farm Control

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Abstract

Feed is one of the largest operational inputs in aquaculture and has a direct influence on production cost, growth performance, feed conversion efficiency, water quality and environmental sustainability. Conventional feeding practices are frequently based on predetermined feeding rates, fixed schedules and farmer experience, which may not adequately account for changes in fish biomass, appetite, behaviour and environmental conditions. Smarter feeding represents a transition towards precision, responsive and data-driven feed management. It combines automatic feeders with real-time information obtained from water-quality sensors, biomass estimation, machine vision, acoustic technologies, Internet of Things (IoT) platforms and artificial intelligence (AI). These technologies enable feeding decisions to be adjusted according to the estimated nutritional demand and feeding response of cultured animals. Machine-vision systems can monitor fish activity, feeding behaviour, size and, in some applications, uneaten feed, while environmental sensors provide information on temperature, dissolved oxygen, pH, salinity and other variables relevant to feeding performance. Integration of these data streams can facilitate dynamic ration adjustment, demand-based feeding and closed-loop control. Such approaches have the potential to reduce feed wastage, improve feed utilization, stabilize water quality and reduce labour requirements. However, practical adoption is constrained by equipment cost, sensor reliability, biofouling, turbidity, species-specific behaviour, data quality, algorithm generalization and the need for farm-level validation. Smarter feeding should therefore be viewed as a decision-support and precision-management framework rather than simply as automated feed dispensing. Future systems are expected to integrate multimodal sensing, AI-based prediction, digital farm records and closed-loop control to achieve increasingly precise and sustainable aquaculture production.

Keywords: Aquaculture; precision feeding; smart feeding; automated feeder; artificial intelligence; machine vision; Internet of Things; feeding behaviour; feed conversion ratio; water quality; precision aquaculture; farm management

1. Introduction

Aquaculture has become an important component of global food production, and efficient feed management is fundamental to the biological and economic performance of cultured aquatic animals. Feed represents a major variable cost in many aquaculture production systems and strongly influences growth, feed conversion ratio (FCR), production efficiency and environmental loading. Consequently, improving the precision with which feed is delivered is an important component of modern aquaculture management.

Traditional feeding practices commonly depend on predetermined feeding rates calculated from estimated biomass, body weight and fish age, together with farmer experience and observation of feeding activity. Such approaches remain practical and widely applicable; however, they may not fully account for the dynamic nature of fish feeding demand. Feeding activity can change in response to temperature, dissolved oxygen, water quality, stress, disease, stocking density, fish size, biomass, feed characteristics and previous feeding history. Therefore, a fixed feeding schedule may result in either inadequate feed supply or unnecessary feed application.

The development of precision aquaculture has created opportunities to improve this situation. Smart feeding systems combine automated feeding equipment with sensors, cameras, communication technologies and computational models to support more accurate feeding decisions. Reviews of intelligent feeding have highlighted the potential of machine vision, behavioural monitoring and automated control for improving feeding management in aquaculture (Zhou et al., 2018; An et al., 2021; Zhang et al., 2023).

The concept of smarter feeding goes beyond replacing manual feeding with an automatic feeder. The principal objective is to develop a responsive feeding system capable of detecting changes in fish demand and adjusting feed delivery accordingly.

2. Concept of Smarter Feeding

Smarter feeding can be defined as:

A data-driven feeding approach in which information on fish biomass, feeding behaviour, environmental conditions and feeding history is used to determine and dynamically adjust the timing, quantity and frequency of feed delivery.

In conventional feeding:

Estimated biomass → Fixed feeding rate → Scheduled feed delivery

In smarter feeding:

Fish/environment monitoring → Data acquisition → Data analysis → Feeding decision → Controlled feed delivery → Observation of response → Adjustment

The second approach introduces a feedback mechanism. The system can therefore respond to changes occurring within the culture environment rather than relying exclusively on predetermined feeding schedules.

3. Why Smarter Feeding Is Required

Several factors justify the development of intelligent feeding systems.

3.1 Feed wastage

Overfeeding can result in uneaten feed accumulating in ponds, tanks or cages. Uneaten feed represents an economic loss and may contribute to organic loading and deterioration of water quality.

3.2 Variable appetite

Fish do not necessarily exhibit the same appetite throughout the day or throughout the production cycle. Feeding response can vary with environmental and physiological conditions.

3.3 Increasing production scale

As farms become larger, continuous manual observation and feeding become increasingly difficult. Automated systems can provide consistent feed distribution across larger production units.

3.4 Labour requirements

Manual feeding requires substantial labour, particularly where several feeding events are conducted daily. Automated feeding can reduce repetitive labour while allowing personnel to focus on supervision and farm management.

3.5 Requirement for real-time farm control

Modern aquaculture increasingly depends on continuous monitoring of production conditions. Feeding systems that communicate with water-quality sensors and farm-management platforms can provide a more integrated management system.

4. Biomass Estimation and Feeding Decisions

Accurate biomass estimation is fundamental to determining feed requirements.

A simplified calculation is:
$$\text{Daily feed requirement (kg)} = \frac{\text{Standing biomass (kg)}}{100} \times \text{Feeding rate (\%)} \times 100$$

For example, a farm containing an estimated 1,000 kg standing biomass with a prescribed feeding rate of 2% biomass per day would have a calculated ration of:
$$1000 \times \frac{2}{100} = 20 \text{ kg day}^{-1}$$

The actual feeding rate must be selected according to the cultured species, size, life stage, feed characteristics, water temperature, culture system and feeding response.

Conventional biomass estimation generally involves periodic sampling. Smart aquaculture systems can supplement manual sampling with camera-based size estimation, fish counting and biomass prediction. Machine-vision research has investigated fish detection, counting and size estimation as components of intelligent feeding systems (An et al., 2021).

5. Monitoring Fish Feeding Behaviour

Feeding behaviour provides valuable information about appetite and feed demand.

Important behavioural indicators include:

- Swimming activity
- Schooling intensity
- Feeding speed
- Surface activity
- Aggregation around feeding areas
- Movement patterns
- Response to feed
- Changes in activity after feeding

Machine-vision systems can convert these behavioural characteristics into measurable parameters. Image-processing and deep-learning techniques can then classify feeding activity and estimate the feeding state of fish.

A simplified decision process is:

High feeding activity + rapid feed consumption → Continue controlled feeding

Reduced feeding activity → Reduce feeding rate

Low feeding activity + uneaten feed → Stop feeding and investigate

This approach allows feeding to be based partly on the biological response of the animals rather than solely on a predetermined ration.

6. Role of Water Quality in Smarter Feeding

Feeding and water quality are closely interconnected. Fish require appropriate environmental conditions for normal metabolism, digestion and feeding behaviour.

Important parameters include:

Water-Quality Parameter	Importance in Feeding Management
Temperature	Influences metabolism and feed demand
Dissolved Oxygen (DO)	Low DO can suppress feeding activity
pH	Influences physiological and culture-system conditions
Ammonia	Elevated concentrations can negatively affect fish
Nitrite	Indicates potential deterioration of water quality
Salinity	Important for osmoregulation and species performance
Turbidity	Can influence feeding behaviour and machine visio

Smart feeding systems can use these parameters as additional information when making feeding decisions.

For example:

Normal environmental conditions + active feeding → Continue feeding

Low dissolved oxygen + reduced activity → Delay/reduce feeding and correct the environmental condition

The objective is not to allow an algorithm to replace the farmer's judgement but to provide additional information for rapid decision-making.

7. Automated Feeding Systems

Automatic feeders are an important foundation of smarter feeding. Basic automated feeders dispense predetermined quantities of feed at programmed times.

More advanced systems can provide:

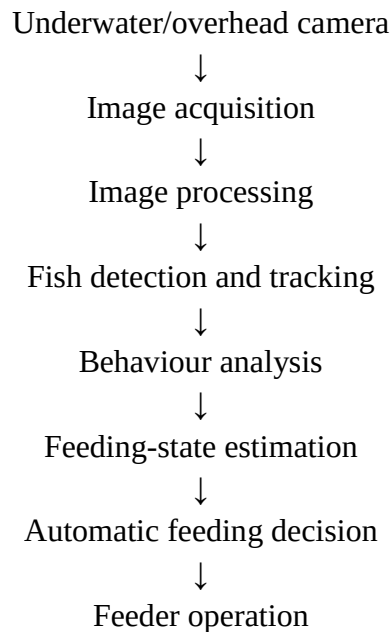
- Multiple feeding events
- Variable feeding rates
- Demand-based feeding
- Remote operation
- Feed consumption monitoring
- Automatic ration adjustment
- Integration with sensors and cameras
- This represents a progression from:
 - Manual feeding → Timer-based feeding → Demand-based feeding → Precision feeding

Recent reviews of aquaculture feeders and intelligent feeding technologies have emphasized the increasing role of automated and demand-responsive systems in modern production (Thornburg, 2025).

8. Machine Vision for Intelligent Feeding

Machine vision is among the most important technologies supporting smarter feeding.

A typical system consists of:



Computer vision can potentially provide information on:

1. Fish number
2. Fish size
3. Biomass
4. Swimming activity
5. Feeding intensity
6. Feed consumption
7. Uneaten feed
8. Abnormal behaviour

Machine-learning and deep-learning techniques have increasingly been investigated for these applications (An et al., 2021; Zhang et al., 2023).

However, performance can be influenced by turbidity, illumination, reflections, fish density, camera position and species-specific behaviour. Therefore, field validation is essential before applying vision-based models at commercial scale.

9. Artificial Intelligence in Smarter Feeding

Artificial intelligence can convert large quantities of farm data into actionable feeding recommendations.

AI models can potentially predict:

- Feeding demand
- Appetite
- Biomass
- Growth
- Feed consumption
- FCR
- Changes in feeding behaviour
- Abnormal feeding patterns

A generalized AI feeding system can be represented as:

Historical farm data + Real-time sensor data + Camera data



AI/ML model



Predicted feeding demand



Feeding recommendation



Automatic or farmer-approved feed delivery

The use of AI is particularly valuable because aquaculture systems generate multiple interacting variables. Instead of relying on one parameter, AI models can identify relationships among environmental conditions, fish behaviour and feeding response.

Nevertheless, AI outputs should be validated against biological observations and farm performance. Models developed under laboratory conditions may not perform equally well under different species, water qualities or production environments.

10. IoT-Based Smart Feeding

The Internet of Things provides the communication infrastructure required to connect farm equipment.

A typical IoT-based feeding system includes:

- Water-quality sensors
- Cameras
- Automated feeders
- Data loggers
- Wireless communication
- Cloud or edge computing
- Farm-management software
- Mobile or web dashboards

The system can provide real-time information regarding:

- Feed quantity
- Feeding time
- Feeding frequency
- Water quality
- Fish activity
- Equipment status
- Historical feeding performance

This enables farmers to supervise multiple culture units remotely and identify unusual conditions more rapidly.

11. Closed-Loop Feeding Control

Closed-loop feeding is an important concept in precision aquaculture.

Open-loop system

The feeding amount is determined in advance.

Feed recommendation → Feeder → Fish

There is limited feedback from the animal after feed delivery.

Closed-loop system

The feeding system continuously observes the response:

Fish → Sensor/camera → Data analysis → Feeding decision → Feeder → Fish response → New feeding decision

This creates a feedback loop.

The objective is to continuously bring feed supply closer to actual feeding demand.

Closed-loop approaches are increasingly discussed as an important direction in precision-feeding technology because they combine sensing, decision-making and automated feed delivery.

12. Feed-Waste Detection

An advanced feeding system can attempt to determine whether feed remains uneaten.

Potential technologies include:

- Underwater cameras
- Optical sensors
- Image analysis
- Acoustic sensing
- Hydrophones

Feed-waste detection can be incorporated into the feeding algorithm:

Feed delivered → Fish response measured → Uneaten feed detected → Feeding reduced/stopped

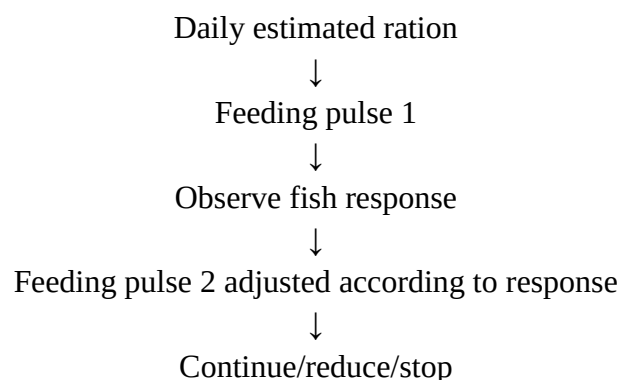
This can reduce unnecessary feed delivery and provide useful information for calculating feeding efficiency.

However, feed particles can be difficult to distinguish from background material under turbid conditions, and therefore sensor selection and calibration are important.

13. Dynamic Feeding Strategy

In smarter feeding, the daily ration can be divided into several controlled feeding events.

For example:



This approach can provide greater control than releasing the entire ration during a small number of large feeding events.

The system should include predetermined safety limits such as:

- Maximum daily ration
- Maximum feeding duration
- Minimum interval between feeding events
- Emergency stop
- Manual override
- Sensor-failure response

These safeguards are particularly important for commercial application.

14. Smarter Feeding and Feed Conversion Ratio

Feed conversion ratio is an important indicator of feed-use efficiency:
$$FCR = \frac{\text{Feed supplied or consumed (kg)}}{\text{Weight gain (kg)}}$$

The exact calculation should be clearly defined in research because apparent FCR and economic FCR may use different components.

Smarter feeding aims to improve feed utilization by reducing:

- Excess feed
- Uneaten feed
- Inappropriate feeding frequency
- Feeding during unfavourable environmental conditions

Improved feed management can consequently contribute to better production economics and lower nutrient wastage.

15. Smarter Feeding for Better Farm Control

The major contribution of smarter feeding is that it connects feeding with broader farm management.

15.1 Production control

Feed data can be linked with biomass and growth data to monitor production performance.

15.2 Water-quality control

Feed input can be considered together with dissolved oxygen, ammonia and other water-quality parameters.

15.3 Economic control

Feed consumption can be monitored against biomass gain and production cost.

15.4 Labour control

Automation reduces repetitive manual feeding operations.

15.5 Risk control

Changes in feeding behaviour can provide an early indication that the culture system requires investigation.

Thus, feeding becomes not simply a routine operation but an important farm-control indicator.

16. Advantages of Smarter Feeding

Parameter	Conventional Feeding	Smarter Feeding
Feeding schedule	Mostly fixed	Dynamic/adjustable
Ration	Predetermined	Potentially responsive

Parameter	Conventional Feeding	Smarter Feeding
Behaviour monitoring	Manual	Automated/continuous
Biomass estimation	Periodic sampling	Sampling + digital estimation
Water-quality integration	Limited	Sensor-based
Feed wastage monitoring	Difficult	Potentially automated
Labour	Relatively high	Reduced
Data collection	Limited	Continuous
Remote monitoring	Limited	Possible
Decision-making	Experience-based	Data-supported
Farm control	Periodic	Real-time/near-real-time

17. Limitations and Challenges

17.1 Initial cost

Smart feeders, cameras, sensors, communication systems and computing equipment may require considerable investment.

17.2 Sensor reliability

Sensors can be affected by:

- Biofouling
- Calibration drift
- Mechanical damage
- Electrical problems
- Communication failure

17.3 Turbidity

High turbidity can reduce the accuracy of underwater vision systems.

17.4 Species-specific differences

Fish species differ considerably in feeding behaviour, swimming patterns and feeding location. Therefore, algorithms may require species-specific calibration.

17.5 Environmental variability

Changes in light intensity, temperature, water quality and weather can affect sensor performance and fish behaviour.

17.6 Data quality

AI models are only as reliable as the data used to develop and validate them.

17.7 Technical skills

Farm workers require appropriate training in operation, calibration, troubleshooting and interpretation of smart-system outputs.

17.8 Overdependence on automation

Automation should support farm management rather than eliminate human observation. Human supervision remains necessary for health assessment, equipment inspection and unexpected events.

18. Practical Framework for Implementing Smarter Feeding

A farm can progressively introduce smarter feeding rather than adopting a fully automated system immediately.

Step 1: Establish baseline information

- Record:
- Species
- Average body weight
- Biomass
- Stocking density
- Feed type
- Daily feed input
- Growth
- FCR
- Water-quality parameters

Step 2: Introduce automated feeding

Use programmable feeders to standardize feed distribution.

Step 3: Add environmental sensors

- Monitor:
- Temperature
- Dissolved oxygen
- pH
- Other species- and system-specific parameters

Step 4: Introduce behavioural monitoring

Use cameras or other appropriate sensing systems to monitor feeding activity.

Step 5: Integrate data

- Combine:
- Biomass + feeding activity + water quality + feeding history
- Step 6: Develop feeding rules or models
- Generate feeding recommendations based on the integrated data.

Step 7: Validate

Compare the smart system with:

- Feed consumption
- Growth
- FCR
- Water quality
- Mortality
- Production cost

Step 8: Introduce closed-loop control

After adequate validation, automatic adjustment of feeding can be implemented within predefined safety limits.

19. Future Perspectives

The next stage of smarter feeding is likely to involve multimodal precision feeding, where several information sources are integrated into one decision-support system.

Future systems may combine:

Machine vision + Water-quality sensors + Acoustic sensing + Biomass estimation + AI + IoT + Automated feeders

This could enable:

- Real-time appetite estimation
- Individual or group biomass prediction
- Dynamic ration adjustment
- Automated feed-waste detect

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