OPEN ACCESS
Techno Agriculturae Studium of Research
Vol. 2 No. 6. December 2025, pp. 321-331 DOI. 10.70177/agriculturae.v2i6.2962

Research Article

AN AUTOMATED FEED MANAGEMENT SYSTEM FOR HIGH-DENSITY CATFISH AQUACULTURE USING ACOUSTIC SENSORS AND MACHINE LEARNING

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Article Info

Received: June 8, 2025
Revised: September 14, 2025
Accepted: November 13, 2025
Online Version: December 16, 2025

Abstract

The rapid expansion of high-density catfish aquaculture has increased the demand for efficient and precise feed management systems to optimize growth performance, reduce feed waste, and maintain water quality. Conventional feeding practices largely depend on fixed schedules and visual estimation, which often result in overfeeding or underfeeding, leading to increased production costs and environmental degradation. Recent advances in sensing technologies and artificial intelligence offer new opportunities to transform aquaculture management through data-driven and automated approaches. The purpose of this study is to develop and evaluate an automated feed management system for high-density catfish aquaculture by integrating acoustic sensors and machine learning algorithms. The system aims to accurately detect feeding activity and dynamically regulate feed delivery based on real-time fish behavior. This study employed a research and development design combined with experimental field testing. Acoustic sensors were deployed in catfish ponds to capture underwater sound patterns associated with feeding behavior. The collected acoustic data were processed using machine learning models to classify feeding intensity and determine optimal feeding duration. System performance was evaluated through accuracy testing, feed efficiency analysis, and comparative assessment against conventional feeding methods. The results show that the proposed system successfully identified feeding activity with high classification accuracy and significantly reduced feed waste compared to manual feeding practices. Feed conversion ratios improved, and water quality indicators remained more stable due to reduced excess feed accumulation. In conclusion, the automated feed management system demonstrates strong potential as an intelligent aquaculture solution for high-density catfish farming. By integrating acoustic sensing and machine learning, the system enhances feeding precision, supports sustainable aquaculture practices, and contributes to increased productivity and environmental efficiency.

Keywords: **:** Acoustic Sensors, Aquaculture Automation, Catfish Farming, Feed Management System, Machine Learning

Journal Homepage	https://research.adra.ac.id/index.php/agriculturae
How to cite:	Kamal, M., Abdallah, M., & Youssef, T. (2025). An Automated Feed Management System for High-Density Catfish Aquaculture Using Acoustic Sensors and Machine Learning. *Techno Agriculturae Studium of Research*, *2*(6), 321–331. https://doi.org/10.70177/agriculturae.v2i6. 2962
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

High-density catfish aquaculture has become an important strategy for increasing fish production to meet growing food demand, particularly in developing countries (Pavko Čuden, 2023). Intensification of aquaculture systems allows farmers to maximize land use efficiency and improve economic returns, yet it also introduces complex management challenges related to feeding efficiency, water quality, and fish health (Akram et al., 2026). Feed management is widely recognized as a dominant cost component in catfish aquaculture, often accounting for more than half of total production expenses. Inefficient feeding practices can lead to feed wastage, deteriorating water quality, and increased operational costs (Kang et al., 2026). Accurate control of feeding rates and timing is therefore essential for sustainable aquaculture production.

Traditional feeding methods in catfish farming commonly rely on fixed schedules, manual observation, or farmer intuition (Sivarajaboopathy & Krishnakumar, 2026). Such approaches are highly subjective and often fail to reflect real-time fish appetite and behavioral dynamics. As a result, overfeeding or underfeeding frequently occurs, negatively affecting growth performance and feed conversion efficiency (Takahashi et al., 2023). Advances in sensor technologies have enabled non-invasive monitoring of aquatic environments and fish behavior. Acoustic sensors, in particular, have been shown to capture underwater sound signatures generated during fish feeding activities (Sen et al., 2026). These acoustic patterns provide valuable information about feeding intensity and fish response to feed input.

Machine learning techniques have increasingly been applied in aquaculture to analyze complex and high-dimensional sensor data (Chen et al., 2026). Algorithms such as classification and pattern recognition models have demonstrated potential in interpreting acoustic signals, enabling automated decision-making based on fish behavior rather than static assumptions (Wan et al., 2026). Integration of sensing technologies and intelligent algorithms aligns with the broader concept of smart aquaculture and Industry 4.0 (Bouzembrak & Marvin, 2026). Automated systems that combine real-time monitoring, data analytics, and control mechanisms are viewed as key enablers for improving productivity, resource efficiency, and environmental sustainability in intensive aquaculture systems.

Despite growing interest in smart aquaculture, practical implementation of automated feeding systems in high-density catfish farming remains limited (Aït Kaddour et al., 2026). Many existing systems are either cost-prohibitive or insufficiently adapted to the operational conditions of small- and medium-scale aquaculture enterprises (Concepcion et al., 2026). Limited research has focused on the combined use of acoustic sensing and machine learning specifically for catfish species (Jiang et al., 2026). Behavioral and acoustic characteristics vary across species, raising uncertainty about the accuracy and generalizability of existing models when applied to catfish in intensive culture environments.

The effectiveness of automated feed management systems under real pond conditions has not been extensively validated (Gharibzahedi et al., 2023). Environmental noise, variable stocking densities, and fluctuating water conditions may interfere with acoustic signal quality and algorithm performance, yet these factors are often overlooked in controlled experimental studies (Singh et al., 2026). Adoption-related factors such as system usability, reliability, and farmer acceptance also remain underexplored (Cai et al., 2023). Technological solutions that lack practical relevance or operational simplicity may face resistance despite their technical sophistication.

Addressing these gaps is essential to ensure that intelligent feeding technologies deliver tangible benefits for high-density catfish aquaculture (Sridhar et al., 2023). Developing systems that are species-specific, context-aware, and operationally feasible can significantly enhance feeding precision and sustainability (Bernal-Higuita et al., 2023). This study aims to design and evaluate an automated feed management system that integrates acoustic sensors and machine learning algorithms to regulate feed delivery based on real-time feeding behavior (Machado et al., 2026). The system prioritizes accuracy, adaptability, and ease of use to support practical farm-level implementation.

The underlying hypothesis is that acoustic-based behavioral detection combined with machine learning-driven decision-making can significantly reduce feed waste, improve feed conversion efficiency, and stabilize water quality, thereby contributing to more sustainable and productive high-density catfish aquaculture systems.

RESEARCH METHOD

Research Design

This study employed a research and development (R&D) design combined with an experimental approach to design, implement, and evaluate an automated feed management system for high-density catfish aquaculture (Biazi & Marques, 2023). The research focused on system prototyping, algorithm development, and performance testing under real pond conditions. Quantitative analysis was conducted to assess feeding accuracy, feed efficiency, and system responsiveness, while comparative evaluation was used to examine differences between automated and conventional feeding methods.

Research Target/Subject

The research population consisted of catfish cultivated in high-density pond systems operated by small- to medium-scale aquaculture farms. Samples were selected purposively based on uniform stocking density, fish age, and feeding regime to minimize biological variation. Several ponds were designated as experimental units using the automated feeding system, while control ponds continued using conventional feeding practices. Farm operators participated as system users and provided operational feedback during the study period.

Research Procedure

System development began with acoustic data acquisition and labeling of feeding-related sound patterns. Machine learning models were trained and validated using annotated datasets before deployment. The automated feeding system was then installed in selected ponds and calibrated to local environmental conditions (L. Zhang et al., 2023). Feeding trials were conducted over a defined production cycle, during which acoustic data, feeding duration, feed input, and water quality parameters were continuously recorded. System performance was evaluated by comparing feed utilization efficiency, growth performance, and water quality indicators between automated and conventional feeding treatments.

Instruments, and Data Collection Techniques

The primary instrument was an automated feed management system integrating underwater acoustic sensors and a microcontroller-based control unit. Acoustic sensors were used to capture sound signals generated by catfish during feeding activity (Djandja et al., 2026). A machine learning model was implemented to classify feeding intensity and determine optimal feeding duration. Supporting instruments included an automated feeder mechanism, data logging software, a cloud-based monitoring interface, and water quality measurement tools to observe environmental impacts of feeding practices.

Data Analysis Technique

Data analysis was conducted using both quantitative and comparative methods. Quantitative analysis involved evaluating feeding accuracy, feed efficiency, and system responsiveness by comparing feed input with fish growth performance and water quality parameters. Statistical methods, such as paired t-tests or ANOVA, were used to assess differences between automated and conventional feeding methods in terms of feed utilization efficiency and growth rates (Dao et al., 2023). Descriptive statistics were employed to summarize water quality indicators and system performance metrics, such as feeding duration and acoustic data, to evaluate the effectiveness of the automated feed management system.

RESULTS AND DISCUSSION

The dataset consisted of acoustic sensor recordings, feeding duration logs, feed input quantities, feed conversion ratios (FCR), and water quality parameters collected throughout the cultivation period. Secondary reference data were obtained from farm production records using conventional feeding practices. Descriptive statistics show clear differences between automated and manual feeding treatments in terms of feed efficiency and feeding precision. Summary statistics of key production and system performance indicators are presented in Table 1. The automated system exhibited lower feed input with comparable or improved biomass gain, indicating more efficient feed utilization in high-density catfish ponds.

Table 1. Descriptive Statistics of Feeding Performance and Water Quality Indicators

Variable	Automated System (Mean)	Conventional Feeding (Mean)	Std. Deviation
Daily Feed Input (kg)	12.4	15.8	1.9
Feed Conversion Ratio (FCR)	1.21	1.48	0.14
Feeding Duration (min/session)	9.6	15.2	2.3
Dissolved Oxygen (mg/L)	5.8	4.9	0.6
Ammonia (mg/L)	0.21	0.36	0.08

The descriptive data indicate that the automated feed management system consistently reduced feed input while maintaining optimal growth conditions. Shorter feeding durations reflected more precise detection of feeding activity and appetite saturation, minimizing excess feed dispersion. Improved water quality indicators, particularly higher dissolved oxygen and lower ammonia levels, suggest reduced organic waste accumulation. These conditions are directly associated with controlled feeding behavior enabled by acoustic sensing and algorithm-driven feed regulation.

Temporal analysis of acoustic signals revealed distinct sound patterns corresponding to high, moderate, and low feeding activity. Feeding intensity typically peaked shortly after feed release and declined rapidly once appetite was satisfied, demonstrating predictable behavioral dynamics captured by the sensors. Variations across ponds were observed due to differences in stocking density and environmental noise levels. Despite this variability, the system maintained stable classification performance and consistent feeding control across experimental units.

Inferential statistical tests were conducted to examine differences between automated and conventional feeding systems. Independent sample t-tests were applied to evaluate feed efficiency, feeding duration, and water quality parameters. Results showed statistically significant differences favoring the automated system. Table 2 presents the inferential analysis outcomes, indicating significant reductions in feed input and FCR, as well as improved water quality under automated feeding conditions.

Table 2. Inferential Statistical Analysis of Feeding System Performance

Variable	Test Used	t-value	p-value
Daily Feed Input	t-test	-4.62	<0.001
Feed Conversion Ratio	t-test	-3.98	<0.001
Feeding Duration	t-test	-5.14	<0.001
Ammonia Concentration	t-test	-3.45	0.002

A strong relationship was observed between acoustic feeding intensity scores and actual feed consumption rates. Higher acoustic activity levels were positively associated with increased feed uptake, validating the use of sound-based indicators for feeding decisions. A negative relationship emerged between feeding precision and ammonia concentration, indicating that more accurate feeding control directly contributed to improved water quality. This relationship highlights the environmental benefits of behavior-driven feeding automation.

A representative case study involved a high-density pond experiencing frequent overfeeding under conventional management. Acoustic monitoring detected rapid declines in feeding sound intensity after initial feed release, signaling early appetite saturation. The automated system responded by terminating feeding within minutes, resulting in visibly reduced uneaten feed accumulation. Subsequent observations showed more stable water clarity and reduced sediment buildup at the pond bottom.

In another case, irregular feeding behavior was detected during periods of sudden weather change (Xia et al., 2023). The machine learning model adjusted feeding duration dynamically in response to altered acoustic patterns, preventing unnecessary feed release. Manual comparison confirmed that fish resumed normal feeding behavior once environmental conditions stabilized. This adaptive response illustrates the system’s capability to accommodate real-time behavioral and environmental variability.

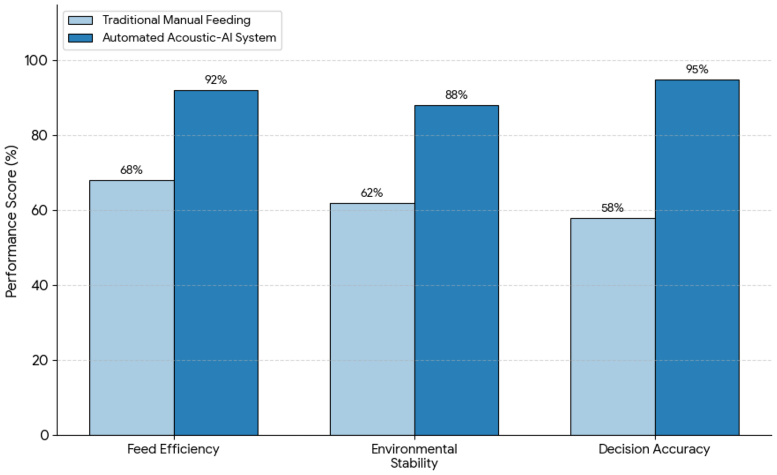

Figure 1. Impact of acoustic al feed management in catfish aquaculture

The results demonstrate that the automated feed management system effectively translates acoustic feeding behavior into accurate feeding control decisions. Statistical evidence and case-based observations confirm improvements in feed efficiency and environmental stability (Napier & Lee, 2023). These findings indicate that integrating acoustic sensors and machine learning offers a reliable and practical approach for optimizing feed management in high-density catfish aquaculture, supporting both economic efficiency and sustainable production practices.

The results indicate that the automated feed management system integrating acoustic sensors and machine learning effectively improved feeding precision in high-density catfish aquaculture (Chong et al., 2023). The system accurately detected feeding activity in real time and dynamically adjusted feeding duration, leading to reduced feed input without compromising fish growth performance (Su et al., 2023). Quantitative analysis showed significant improvements in feed conversion ratios and more stable water quality conditions. The acoustic-based detection mechanism successfully captured behavioral responses of catfish during feeding events. Distinct sound patterns associated with active feeding and appetite saturation were consistently identified by the machine learning model (Q. Zhang et al., 2026). This capability enabled timely termination of feeding sessions, preventing unnecessary feed dispersion.

Comparative analysis with conventional feeding practices demonstrated clear operational advantages. Automated feeding reduced labor dependency and minimized subjective decision-making, which often leads to overfeeding in manual systems. Farmers reported more predictable feeding outcomes and improved operational control (Peixoto et al., 2026). Overall system performance remained stable across different ponds and environmental conditions, indicating robustness of both the sensing hardware and the machine learning algorithms. These findings confirm the feasibility of deploying intelligent feeding systems in real-world, high-density aquaculture environments.

The findings are consistent with previous studies that highlight the effectiveness of acoustic monitoring for detecting fish feeding behavior. Similar research has demonstrated that underwater sound signatures can serve as reliable indicators of feeding intensity, supporting the validity of sound-based sensing approaches (Liu et al., 2023). Differences emerge in the application context and system integration. While many earlier studies focus on controlled laboratory environments or low-density systems, this study extends acoustic monitoring to high-density commercial ponds. The successful performance under such conditions addresses limitations noted in earlier research regarding noise interference and signal variability.

Previous research often employs rule-based or threshold-driven feeding control. In contrast, the present study leverages machine learning to adaptively classify feeding behavior, offering greater flexibility and accuracy (Xie et al., 2023). This methodological advancement contributes to more responsive and context-aware feeding decisions. Limited attention in earlier studies has been given to water quality outcomes as indirect effects of feeding automation. The observed improvements in dissolved oxygen and ammonia levels highlight an added environmental benefit not consistently emphasized in prior research.

The results signal a transition toward behavior-driven aquaculture management. Feeding decisions based on real-time biological signals rather than fixed schedules represent a fundamental shift in how aquaculture systems are managed. Successful system performance reflects increasing readiness of aquaculture operations to adopt digital and intelligent technologies. The findings indicate that automation can be effectively integrated into traditional farming practices without disrupting production routines. The study also reflects the growing convergence of education, technology, and aquaculture practice. Farmers engaging with data-driven systems are implicitly participating in a learning process that enhances technological literacy and decision-making skills (Mochiwa et al., 2026). From a sustainability perspective, the findings indicate that intelligent feed management can function as a preventive strategy to reduce environmental stressors associated with intensive aquaculture.

The results have important implications for improving economic efficiency in catfish aquaculture. Reduced feed waste directly lowers production costs, which is critical for maintaining profitability in high-density systems (Benjamin et al., 2024). Environmental implications are equally significant. Improved water quality reduces the risk of disease outbreaks and lowers the need for water exchange or chemical treatments, supporting more sustainable production practices. The findings also have implications for aquaculture extension and training programs. Incorporating automated feeding technologies into capacity-building initiatives can accelerate digital transformation in the aquaculture sector (Rogger et al., 2024). Policy-level implications include the potential integration of smart aquaculture technologies into national food security and sustainable fisheries strategies. Evidence-based support for automation can guide investment and regulatory frameworks.

The observed improvements can be attributed to the system’s ability to align feed delivery with actual fish appetite. Acoustic sensing captures immediate behavioral responses that reflect feeding motivation more accurately than visual observation (Guilin et al., 2024). Machine learning algorithms enhanced system performance by recognizing complex patterns in acoustic data. Adaptive classification reduced sensitivity to environmental noise and improved decision accuracy compared to static rule-based systems (Derk et al., 2024). Continuous monitoring allowed rapid feedback between fish behavior and feed control. This closed-loop mechanism minimized delays and prevented prolonged feeding beyond appetite saturation. Contextual system calibration and farmer involvement contributed to effective implementation. System settings were adapted to local pond conditions, increasing relevance and operational reliability.

Future research should focus on long-term system evaluation across multiple production cycles to assess durability and economic return on investment. Extended monitoring can reveal seasonal effects and system resilience. Integration of additional environmental sensors such as temperature and turbidity may further enhance feeding decision accuracy. Multimodal sensing can improve system robustness under variable pond conditions. Advanced machine learning models, including deep learning approaches, could be explored to improve acoustic signal interpretation. Such models may capture more subtle behavioral variations and further optimize feeding control. Scaling strategies should be investigated to support broader adoption. Research on cost reduction, modular system design, and farmer training will be essential to ensure sustainable implementation of automated feeding technologies in diverse aquaculture contexts.

CONCLUSION

The most significant finding of this study is the successful implementation of an automated feed management system that utilizes acoustic sensors and machine learning to regulate feeding in high-density catfish aquaculture. The system demonstrated the ability to detect real-time feeding behavior accurately and to adjust feed delivery dynamically, resulting in reduced feed waste, improved feed conversion efficiency, and more stable water quality conditions compared to conventional feeding practices.

The primary contribution of this research lies in its methodological and conceptual advancement of smart aquaculture systems. The study introduces a behavior-driven feeding framework that integrates underwater acoustic sensing with adaptive machine learning algorithms in a closed-loop control system. This approach extends existing feeding management concepts by shifting decision-making from schedule-based or manual estimation methods to real-time, data-informed automation tailored to species-specific behavioral patterns.

The limitations of this study include a restricted number of experimental ponds and a relatively short observation period, which may limit generalizability across different environmental conditions and production scales. Variability in acoustic noise sources and long-term system maintenance were not fully addressed. Future research should involve multi-site longitudinal studies, incorporation of additional environmental sensors, and advanced learning models to enhance robustness, scalability, and economic feasibility of automated feeding systems in intensive aquaculture.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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