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Effects of Novel Smart-Assisted Automatic Fish Feeder on Growth Parameters and Cost Effectiveness in African Catfish *Clarias Gariepinus* Juveniles Farming

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ABSTRACT

This study evaluated the effect of a novel smart-assisted automatic fish-feeding system on the growth performance and cost-effectiveness of African catfish during a 56-day trial. Fifty fish were stocked in two 500 L concrete tanks of 1m by 1m by 0.5m at 25 fish per treatment. Treatment one (T1) served as the manually fed control, while Treatment (T2) received smart-assisted feeding. The experiment was duplicated at two scheduled meals, 3% biomass, at real-time water-temperature input and a Q10-based adjustment. A commercial diet containing 45.0% crude protein and 14.0% crude lipid, with calculated gross energy of 21.52 kJ/g was used. Water quality parameters were monitored and did not differ significantly between treatments. T2 produced higher final weight, weight gain, average daily gain, specific growth rate and percentage weight gain, with $p = .003$ for each comparison. Survival was 100% in T1 and 96% in T2. Feed conversion ratio was lower in T2 (2.39) than in T1 (3.09; $p = .004$). Total relevant operating cost was ₦20,541.41 for manual feeding and ₦20,785.99 for SmartAQUA, while cost per kilogram of biomass gain was ₦5,888.44 and ₦4,898.29, respectively. The additional 0.755 kg of biomass gain required an incremental operating cost of ₦244.58, equivalent to ₦323.91 per additional kilogram gained. The results show that SmartAQUA improved feeding-time compliance, labour efficiency, feed conversion and operating cost per kilogram of biomass gain. The results indicated that the novel SmartAQUA improved growth and most feed- and nutrient-utilisation indices under the conditions of the study.

Keywords: African catfish; automatic feeder; feed conversion; nutrient retention; Q10; SmartAQUA.

INTRODUCTION

Aquaculture has become central to the global supply of aquatic foods. In 2022, farmed aquatic animals exceeded capture-fisheries production for the first time, demonstrating the increasing importance of efficient and sustainable production systems (Food and Agriculture Organization of the United Nations, 2024). This expansion, however, places greater attention on how farms manage feed, labour, energy, water quality and production records because avoidable losses at the farm level weaken both profitability and environmental performance.

Nigeria is the second-largest aquaculture producer in Africa, and its farmed-fish sector is strongly associated with African catfish, *Clarias gariepinus*. The species is widely cultured because of its rapid growth, tolerance of intensive production conditions, ability to use formulated diets and strong consumer acceptance.

Nevertheless, domestic fish supply remains below demand, and the expansion of catfish farming is constrained by variable input prices, limited technical support, inconsistent management and uneven adoption of reliable production technologies (Ogunji and Wuertz, 2023; Srikulnath *et al.*, 2025).

Feed is the most frequently supplied input during an intensive feeding cycle and commonly represents the largest recurrent cost of production. A feeding error therefore has immediate economic consequences. Overfeeding increases the amount of feed purchased without a corresponding increase in harvestable biomass, whereas underfeeding can suppress growth, increase size variation and extend the production period. Efficient ration calculation and consistent delivery are consequently essential to the profitability of African catfish culture (Langi *et al.*, 2024; Thornburg, 2025). Manual feeding remains common in small and medium aquaculture enterprises because it requires little specialised equipment and permits the farmer to observe fish directly. Its performance, however, depends on the accuracy, availability and consistency of the operator. Variations in feeding time, ration measurement and distribution can introduce avoidable differences in feed intake and growth. Automatic feeders were developed to reduce this variability by delivering measured quantities at programmed times, while contemporary smart feeders add sensing, communication and software-based decision rules to conventional automation (Khater *et al.*, 2021; Thornburg, 2025).

The feeding response of fish is not independent of the culture environment. *Clarias gariepinus* is ectothermic, so water temperature affects metabolic rate, digestion, gastric emptying and feed utilization. Recent work on African catfish showed that temperatures between 26 and 32 degrees Celsius influenced feed conversion and gastric emptying even where several gross growth indices did not differ significantly. A fixed ration can therefore become less suitable when water temperature moves away from the reference condition used to determine the ration (Kasihmuddin *et al.*, 2021; Langi *et al.*, 2024).

The study is justified by the need to improve feed accountability in concrete-tank catfish farming. A calibrated feeder can convert a target ration into a repeatable number of motor steps, while event logs can show whether the scheduled feeding occurred and how much feed was commanded. Dispensing accuracy, timing deviation, delivery consistency and event completion therefore provide direct evidence of feed-management performance beyond simply describing the feeder as functional (FAO, 2013).

The work is also relevant to labour management. Manual feeding requires feed weighing, movement to the tank, distribution, observation, cleaning and record keeping twice daily. Smart-assisted feeding transfers most routine delivery to a scheduled electromechanical system, although hopper filling, inspection, cleaning and programming remain necessary. A time-and-motion assessment and the prevailing daily farm wage allow these activities to be converted directly into comparable person-hours and monetary labour costs.

An economic evaluation is necessary because a technically accurate device may still be unsuitable for a small farm. The novel SmartAQUA system adds hardware and communication requirements. These must be compared with feed cost, labour cost, incidence cost, total relevant cost per kilogram of biomass gain and cost per surviving fish. Linking feed expenditure with protein, lipid and dietary energy retained in the fish further shows whether the system used purchased nutrients economically (Olagunju *et al.*, 2022, 2024).

A smart feeding system should, however, be evaluated as an aquaculture intervention rather than only as an engineering prototype. This requires a direct comparison between the smart-assisted method and the manual practice under the same feed, stocking, tank and husbandry conditions (Dorgham *et al.*, 2025; Thornburg, 2025). This current study therefore evaluates a novel SmartAQUA feeder that combines a waterproof DS18B20 sensor for real-time water-temperature input; an ESP32-based LILYGO T-A7670E controller with LTE cellular communication; a stepper-motor-driven auger dispenser; MQTT messaging over the cellular network, reducing dependence on farm Wi-Fi; a cloud backend for schedules, telemetry, commands and persistent feeding records; and a Flutter mobile application for device binding, monitoring, schedule management, manual control and feeding history. These functions are linked to a bounded Q10 ration-adjustment algorithm that uses Q10 = 2.1 at a 25°C reference temperature, constrains the positive adjustment factor to 0.3-2.0, applies a reduced ration below 20°C, progressively reduces the calculated ration between

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32°C and 36°C, and stops feeding at or above 36°C. It focused on whether the implemented system can support the growth performance and nutrient utilization of African catfish during an eight-week feeding trial.

MATERIALS AND METHODS

Study Area

The study was undertaken at the Federal University of Technology, Akure, Ondo State, Nigeria. Mechanical fabrication and assembly were carried out with the support of the Agricultural Engineering workshop, software and data-related development were coordinated through the Computer Science digital laboratory, and the feeding trial was conducted at the Teaching and Research Fish Farm of the Department of Fisheries and Aquaculture Technology.

Experimental Design

The experiment was conducted as a two-treatment, two-tank comparison. Two 500 L concrete tanks (1m by 1m by 0.5m) were used, with one tank assigned to each feeding method. Treatment one (T1) served as the manually fed control, while Treatment (T2) received smart-assisted feeding. The experiment was replicated in duplicate. Twenty-five African catfish were stocked in each tank, giving an initial total of 50 fish, and the feeding trial lasted eight weeks, equivalent to 56 days.

Both tanks received the same commercial feed and the same baseline daily ration of 3% of the most recent live tank biomass, divided into two meals. T1 received the calculated ration manually, whereas T2 received a ration delivered by SmartAQUA and adjusted by the implemented temperature-response logic. The independent variable was therefore the integrated feeding strategy, which combined delivery method and temperature adjustment in T2. The Experimental Layout of T1 and T2 is displayed in Figure 1.

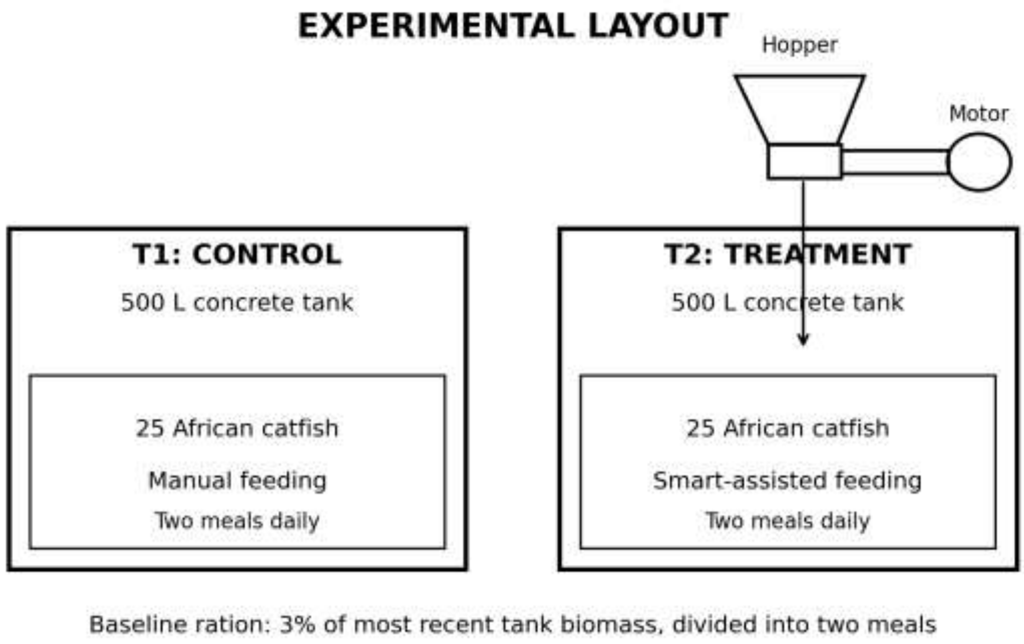

Figure 1: Experimental Layout of T1 and T2

Experimental Fish and Acclimation

Fifty juvenile African catfish were kept together in a holding tank for a two-week acclimatisation period and were fed ad libitum. At the end of acclimatisation, the fish were fasted before measurement, weighed and distributed into the respective concrete culture units designated Pond 1 or T1 and Pond 2 or T2. Twenty-five

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fish were stocked in each unit. The initial tank mean weights used for biomass calculation were 249.27 g/fish for T1 and 249.39 g/fish for T2. Fish handling was minimised, and surviving numbers were used in subsequent biomass and feed-per-fish calculations.

Experimental Feed and Feeding Protocol

Feed was stored in a dry, covered location and weighed using the same scale throughout the trial (Langi *et al.*, 2024; Phan *et al.*, 2022).

$$DF = 0.03 \times B_t$$

$$F_m = \frac{DF}{2}$$

In T1, each meal was weighed, supplied manually, and recorded with its actual feeding time and for T2, the feeder schedule was set for 09:00 and 17:00 WAT, and the base meal was adjusted using the current valid temperature according to the Q10 and thermal safety.

Hardware Components of the novel SmartAQUA System

The LILYGO T-A7670E R2 served as the principal controller. The board combines an ESP32-WROVER-E microcontroller with an A7670E LTE Cat-1 modem, which allowed the feeder to execute local control functions and communicate through the cellular network. In the implemented system, it read the DS18B20 sensor, generated motor-control signals and exchanged MQTT messages with the cloud service (LILYGO, 2026; Akhter *et al.*, 2021). The principal components and representative component images are presented in Figure 2.

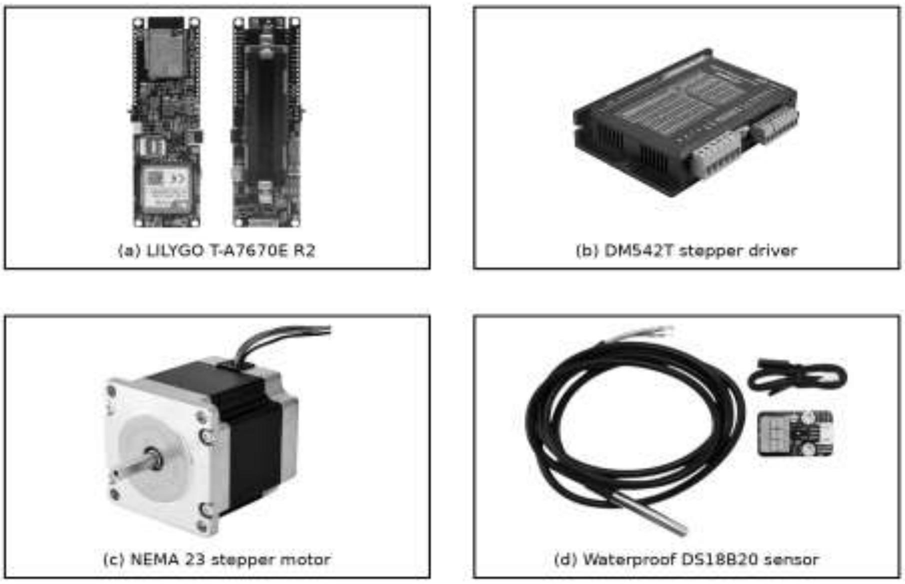

Figure 2: Principal Hardware Components Used in the SmartAQUA System

Source: Product images from LILYGO (2026), StepperOnline (2026a, 2026b) and DFRobot (2026).

System Architecture and Operation

The SmartAQUA platform operated through four connected layers: embedded firmware, MQTT communication, a cloud backend and a mobile application. The controller read the DS18B20 sensor, checked the feeding schedule, applied the applicable temperature rule, generated the step pulses required for dispensing

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and transmitted timestamped sensor and feeding events (Akhter *et al.*, 2021; Yang *et al.*, 2021). Feed adjustment was performed by the backend or firmware, while the mobile application displayed Q10 information without determining the quantity dispensed. The complete operational architecture is shown in Figure 3.

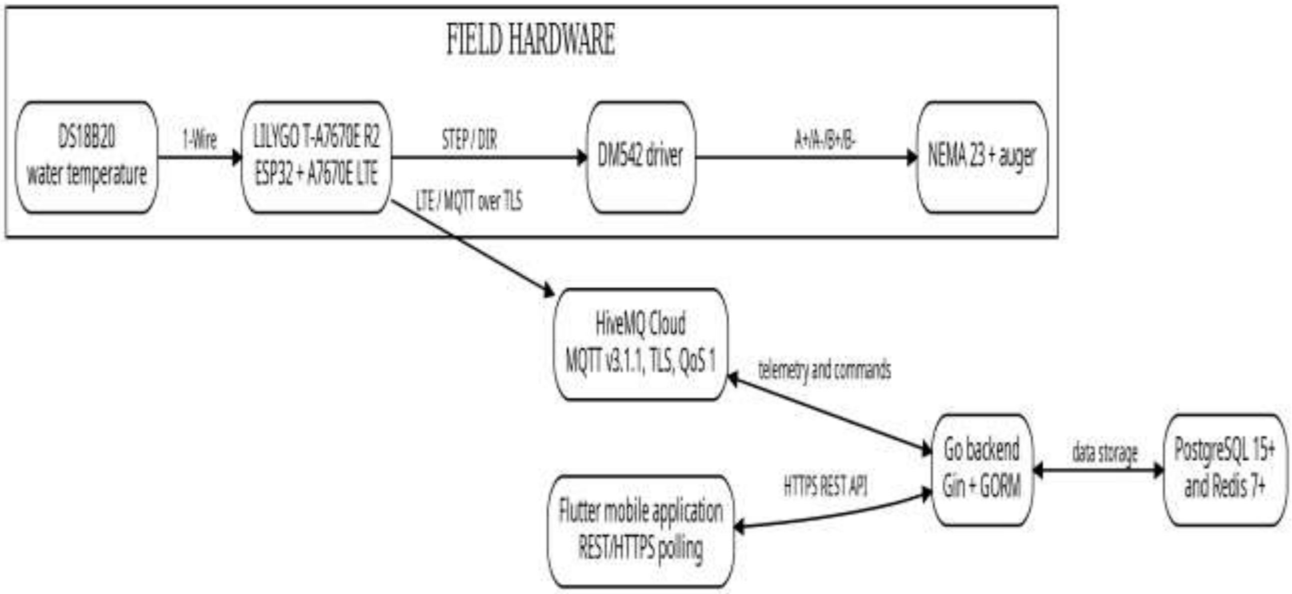

Figure 3: SmartAQUA System Architecture

The dispensing assembly consisted of a feed hopper mounted above a horizontal barrel containing the auger. Pellets entered the barrel by gravity, and the auger transported them toward the forward outlet. Figure 4 showed the relative positions of the hopper, barrel, auger, motor and forward outlet used in the system (Khater *et al.*, 2021; Thornburg, 2025).

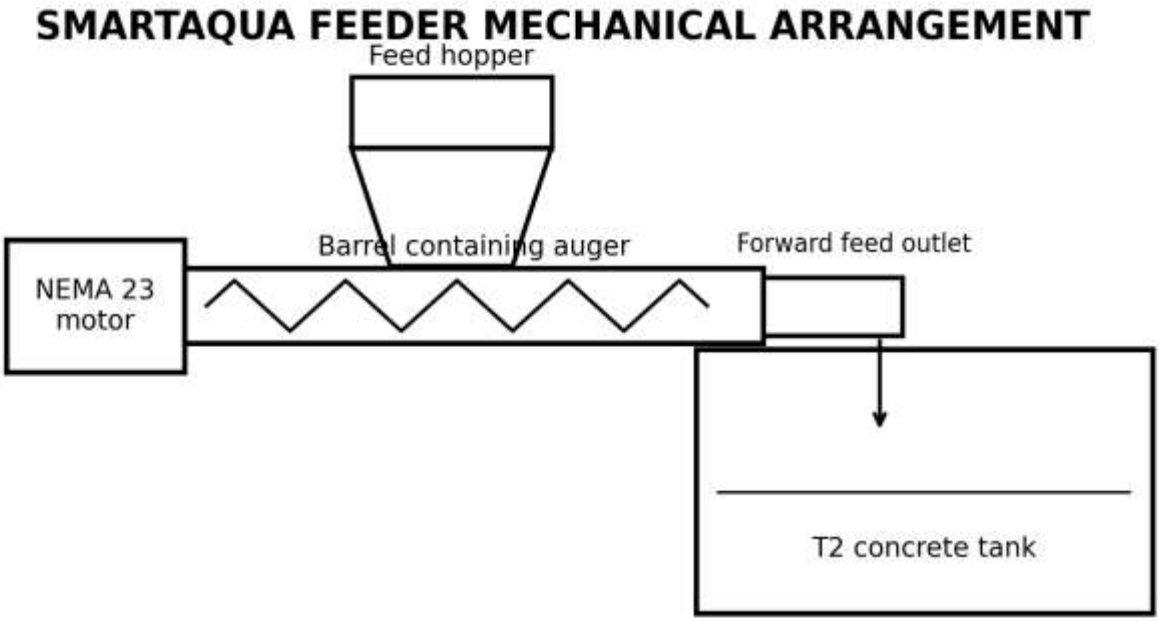

Figure 4: Mechanical Arrangement of the SmartAQUA Feeder

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Electrical Circuit and Production Pin Map

The complete circuit diagram in Figure 5 was developed using EasyEDA. The GPIO net labels follow the production firmware assignments: GPIO32 for MOTOR_STEP, GPIO18 for MOTOR_DIR, GPIO0 for FEED_BTN, GPIO2 for LED_STATUS and GPIO14 for the DS18B20 DATA line (EasyEDA, 2025; LILYGO, 2026).

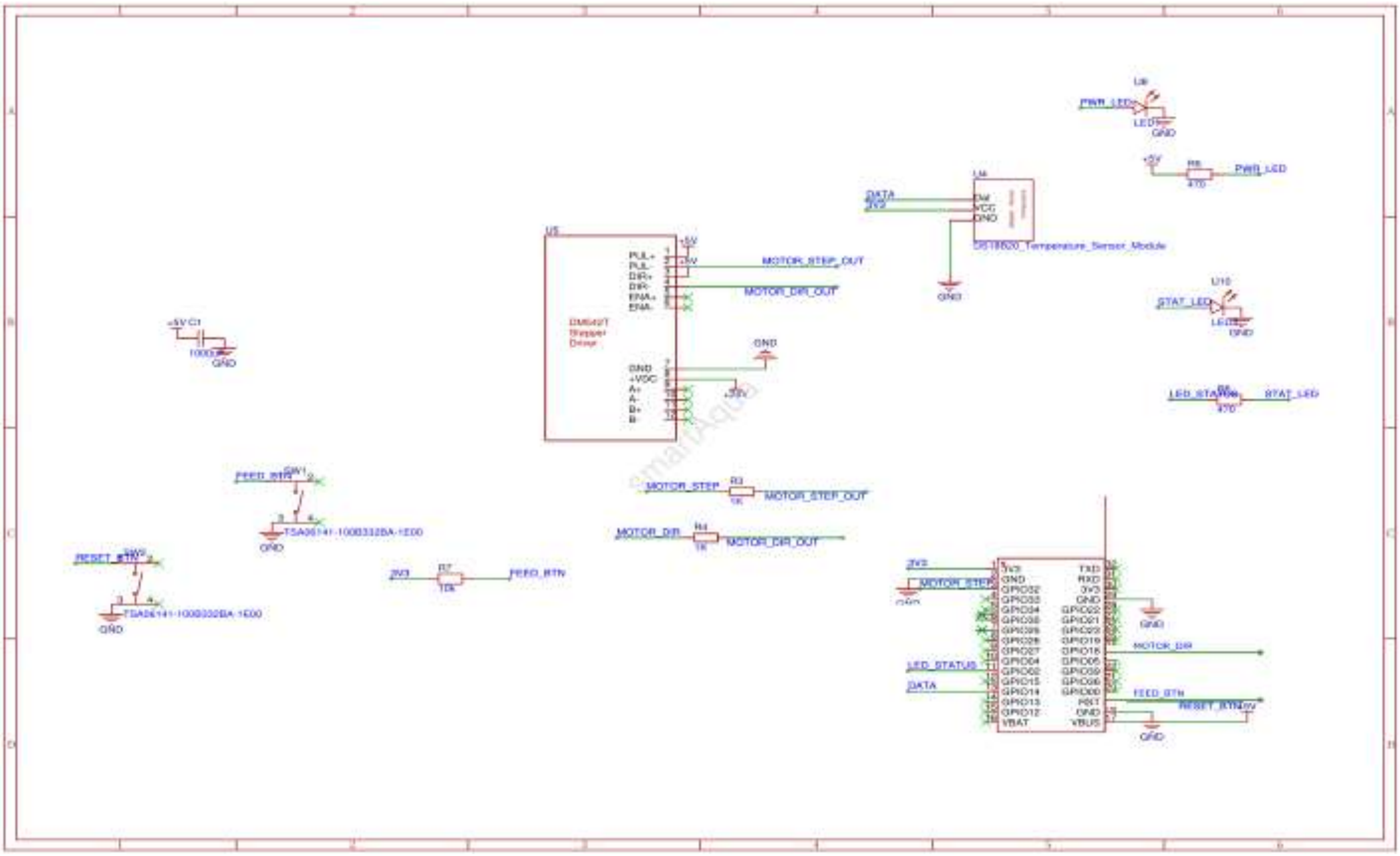

Figure 5: Complete Circuit Diagram of the SmartAQUA Feeder Designed in EasyEDA

Q10 Temperature-Adjusted Feeding Algorithm

The decision sequence is shown in Figure 6. The T2 feeding algorithm used a Q10 value of 2.1 and a reference temperature of 25 degrees Celsius. The raw temperature factor was calculated by raising 2.1 to the power of the temperature difference divided by 10 and was constrained to the interval 0.3 to 2.0 (Mundim *et al.*, 2020; Kasihmuddin *et al.*, 2021). Thermal safety limits were applied before dispensing. Feeding stopped when T was at least 36 degrees Celsius. Between 32 and 36 degrees Celsius, the ration was reduced linearly from the calculated amount toward zero.

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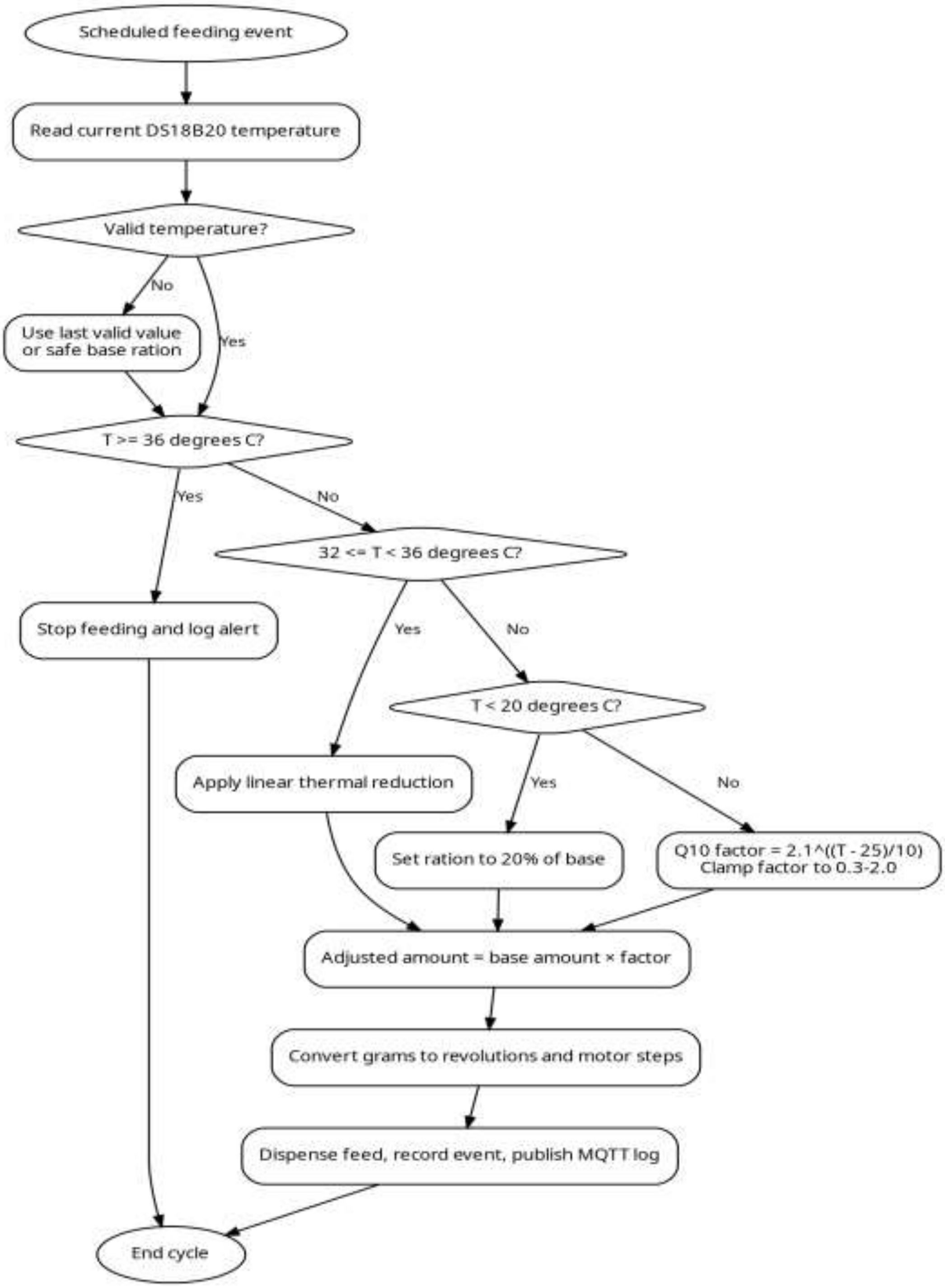

Figure 6: Q10 Temperature-Adjusted Feeding Control Flowchart

Motor Control and Feed Calibration

The NEMA 23 motor was rated at 200 full steps per revolution and was configured for half-step operation, giving 400 effective steps per revolution. Feed delivery was calibrated at 10.45 g per auger revolution. The control sequence is shown in Figure 7 (Khater *et al.*, 2021; Percie du Sert *et al.*, 2020).

$$R = \frac{M_t}{G_{rev}}$$

$$S = R \times S_{rev}$$

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$$t_d = \frac{S}{S_s}$$

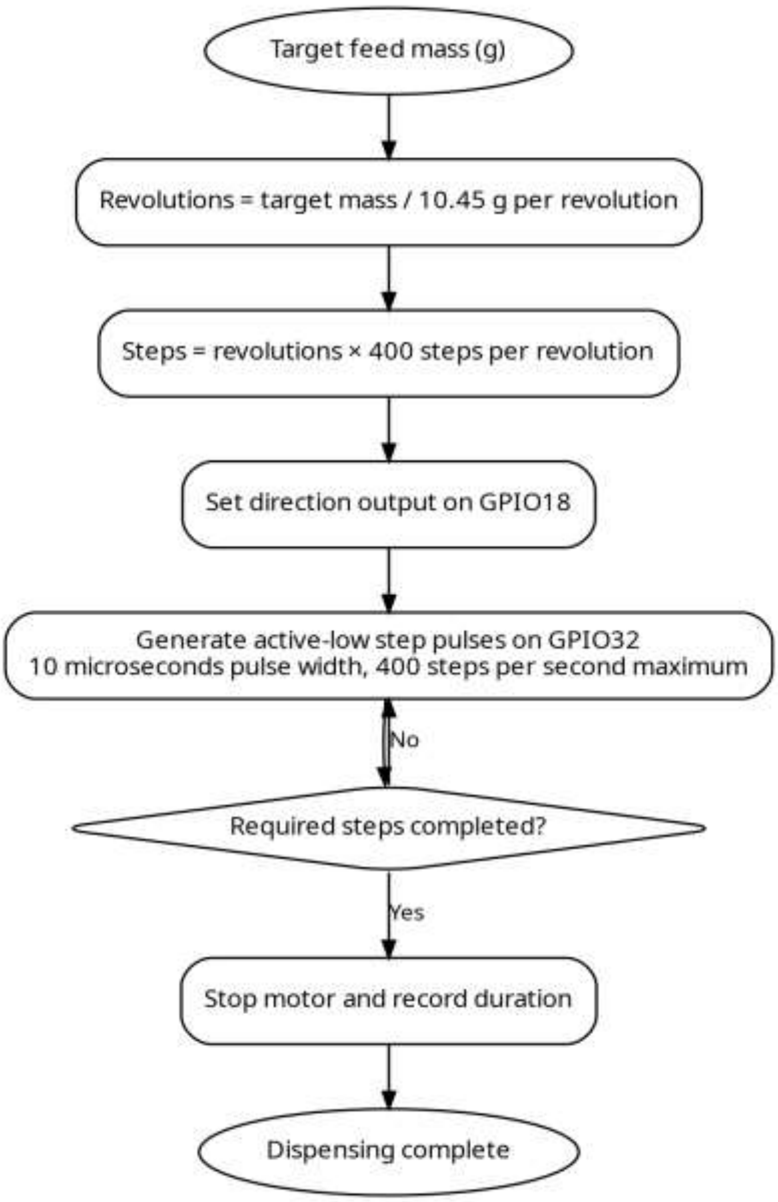

Figure 7: Motor Control and Feed Dispensing Flowchart

Water quality parameters

The water quality parameters (temperature, pH, conductivity, dissolved oxygen) of the water used for the experiment were determined and documented during the experiment. This was done weekly by taking the water samples from fish tanks using well labelled airtight containers and these parameters were measured in the limnology laboratory of the Department of Fisheries and Aquaculture Technology, Federal University of Technology, Akure, Ondo State. Determination of water quality parameters of water was done using a HANNA HI98494 (Poland) multi parameter water checker instrument.

Proximate analyses of fish carcasses

Proximate analyses of the fish were performed according to the procedure of the AOAC (2023), at the Centre laboratory of the Federal University of Technology, Akure. Ondo.

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Growth Performance Calculations

The fish were weighed at each sampling point, and mean weight was calculated for each treatment. Treatment mean values were used for all growth-performance calculations. Weight gain, percentage weight gain, average daily gain and specific growth rate were calculated from the relevant initial and final treatment mean weights. The duration was 56 days for final indices and the exact elapsed interval for intermediate calculations. Natural logarithms were used for specific growth rate, and all units were stated with the result (Langi *et al.*, 2024).

$$WG = W_2 - W_1$$

$$PWG\ (\%) = \frac{W_2 - W_1}{W_1} \times 100$$

$$ADG = \frac{WG}{t}$$

$$SGR = \frac{\ln W_2 - \ln W_1}{t} \times 100$$

$$SR\ (\%) = \frac{N_2}{N_1} \times 100$$

In the growth formulas, W1 and W2 are the initial and final treatment mean weights, t is the culture period in days, and N1 and N2 are the initial and final fish numbers (Langi *et al.*, 2024; Quirós-Pozo *et al.*, 2023).

Feed and Nutrient Utilization Calculations

Cumulative feed supplied was obtained by summing the recorded feed mass for each treatment. Feed intake per fish was calculated by dividing total feed supplied by the number of surviving fish. The recorded feed values were used to calculate feed conversion ratio and feed conversion efficiency (Thornburg, 2025; Shaw *et al.*, 2022).

$$FI = \frac{F_s}{N_s}$$

$$FCR = \frac{F_s}{BWG}$$

$$FCE\ (\%) = \frac{BWG}{F_s} \times 100$$

In the feed-use formulas, Fs is cumulative feed supplied, Ns is the number of surviving fish, FI is feed intake per fish, BWG is biomass weight gain, FCR is feed conversion ratio and FCE is feed conversion efficiency (Thornburg, 2025).

Carcass Composition Analysis

Nitrogen-free extract was calculated by difference. Gross energy was calculated as GE (kJ/g) = [23.6(CP) + 39.5(CL) + 17.2(NFE)]/100, where CP, CL and NFE are expressed as percentages. These values were used for nutrient-utilization calculations (AOAC International, 2023; Phan *et al.*, 2022).

Cost and Cost-Effectiveness Calculations

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Feed Price, Feed Cost and Incidence Cost

The same confirmed price was used for the 3-mm and 4-mm Skretting feed phases. One 15-kg bag cost ₦26,000, giving a unit feed price of ₦1,733.33 per kilogram. The reference fish price was ₦3,000 per kilogram and was retained as contextual market-price information only.

$$P_f = \frac{C_b}{W_b} = \frac{₦26{,}000}{15\,\mathrm{kg}} = ₦1{,}733.33\,\mathrm{kg}^{-1}$$

$$TFC = F_s P_f$$

$$P_{\mathrm{fish}} = ₦3{,}000\,\mathrm{kg}^{-1}$$

C_b is the price of one feed bag, W_b is the 15-kg bag weight, F_s is the total quantity of feed supplied, Pf is the unit feed price, Pfish is the reference price per kilogram of fish and TFC is total feed cost. Incidence cost and related comparisons were:

$$IC = \frac{TFC}{BWG}$$

$$FCS = IC_M - IC_S$$

$$ICR(\%) = \frac{IC_M - IC_S}{IC_M} \times 100$$

$$FCF = \frac{TFC}{N_f}$$

A positive feed-cost saving or percentage reduction indicates that SmartAQUA lowered the feed expenditure required to produce one kilogram of biomass gain.

Labour Cost, Savings and Productivity

Representative time per feeding event was 4 minutes for manual feeding and 5 seconds for SmartAQUA. These values were multiplied by 96 feeding events to estimate the 56-day labour requirement.

Person-hours for each activity and total labour hours were determined as follows:

$$PH_i = \frac{N_i t_i}{60}$$

$$TLH = \sum_{i=1}^{n} P\,H_i$$

$$LC = \frac{TLH}{H_d} W_d$$

N_i is the number of workers, t_i is activity duration in minutes, W_d is the prevailing daily wage and Hd is the standard working day in hours. Labour cost was calculated directly from the proportion of a standard workday used by each method:

$$LC_M = \frac{TLH_M}{H_d} W_d$$

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$$LC_S = \frac{TLH_S}{H_d} W_d$$

Labour-time and labour-cost savings were:

$$LTS = TLH_M - TLH_S \; LTR(\%) = \frac{TLH_M - TLH_S}{TLH_M} \times 100$$

$$LCS = LC_M - LC_S$$

$$LCR(\%) = \frac{LC_M - LC_S}{LC_M} \times 100$$

Labour cost and productivity relative to production outputs were:

$$LCF = \frac{LC}{F_s}$$

$$LCBG = \frac{LC}{BWG}$$

$$LC_{\text{fish}} = \frac{LC}{N_f}$$

$$LP = \frac{BWG}{TLH}$$

Capital Cost

The initial SmartAQUA investment was recorded as the sum of hardware, fabrication and installation costs. Construction, fabrication and installation cost ₦240,000 and additional capital/component expenditure was ₦38,000, giving a total recorded prototype investment of ₦278,000. Capital cost was presented separately as the acquisition cost of the prototype and was not included in the 56-day total relevant operating cost.

$$C_0 = \sum_{h=1}^{q} C_h + C_{\text{fab}} + C_{\text{inst}}$$

Total Relevant Operating Cost and Cost-Effectiveness

The total relevant operating cost was calculated separately for each feeding method from feed, labour and communication expenditure. Prototype acquisition cost was reported separately and was not included in this comparison.

TRC = TFC + LC + CC

CC is the recorded cellular or communication cost. TRC includes only feed cost, labour cost and communication cost for the feeding methods. Because complete fingerling, water, medication and other husbandry costs were not available, TRC is described as total relevant operating cost rather than complete production cost.

$$CRBG = \frac{TRC}{BWG}$$

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$$CRSF = \frac{TRC}{N_f}$$

$$\Delta C = TRC_S - TRC_M$$

$$CS = TRC_M - TRC_S$$

$$TCR(\%) = \frac{TRC_M - TRC_S}{TRC_M} \times 100$$

Positive cost saving and percentage cost reduction indicate a lower relevant cost under SmartAQUA.

Statistical Analysis

Data were expressed as mean ± standard deviation and analysed using IBM SPSS Statistics, version 32 for Windows. For variables with non-zero within-treatment variance, T1 and T2 were compared using one-tailed independent-samples t-tests, and significance was accepted at $p < 0.05$. Equal-variances-assumed results were reported at df = 2 for growth, carcass and nutrient indices and at df = 6 for the water-quality variables.

Ethical and Safety Considerations

All experimental procedures were approved by the Animal Care and Use Committee (Approval No. (FUTA/ETH/24/167). This study adheres to internationally accepted standards for animal research, following the 3Rs principle. The Animal Scientific guidelines were employed to report experiments involving live animals and promote ethical research practices.

RESULTS

Water Quality Parameters

The water-quality results for the manually fed treatment, T1 (MA), and the smart-assisted treatment, T2 (AU), are presented in Table 2. Conductivity, pH, dissolved oxygen and temperature did not differ significantly between the treatments on the one-tailed tests ($p > 0.05$).

Table 2: Water-Quality Parameters in the Two Feeding Treatments

Parameter	**T1 (MA)**	**T2 (AU)**	**t**	**p**	**Inference**
Conductivity (µS/cm)	505.75 ± 106.79	501.25 ± 172.41	0.044	0.483	Not significant
pH	7.14 ± 0.13	7.11 ± 0.05	0.502	0.317	Not significant
Dissolved oxygen (mg/L)	5.58 ± 1.43	5.35 ± 1.51	0.217	0.418	Not significant
Temperature (°C)	25.75 ± 0.30	25.75 ± 0.31	0.000	0.500	Not significant

Values are mean ± SD. The p values are from one-tailed tests; equal-variances-assumed results are reported at df = 6. Source: Experimental data and IBM SPSS Statistics version 32 output of the present study.

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Initial Carcass, Final Carcass Composition and Feed and Nutrient Utilisation Composition

The initial carcass composition values was as follows: Crude protein was 70.893% in T1 and 75.431% in T2. The calculated gross energy values were 20.60 kJ/g and 20.84 kJ/g, respectively. These initial values provide the baseline composition required for subsequent nutrient-retention calculations. Final carcass moisture was 6.14 ± 2.93% in T1 and 5.64 ± 0.52% in T2, and the difference was not significant ($p = .417$). Crude protein and ash also did not differ significantly between the treatments ($p = .337$ and $p = .072$, respectively). Final crude lipid was significantly higher in T2 (18.15 ± 0.49%) than in T1 (16.65 ± 0.21%; $p = .029$).

Nitrogen-free extract, recalculated by difference after including moisture, was 6.06 ± 6.18% in T1 and 3.31 ± 0.45% in T2 ($p = .297$). Formula-derived gross energy was 22.29 ± 0.33 kJ/g in T1 and 22.64 ± 0.10 kJ/g in T2, and the difference was not significant ($p = .140$), as presented in Table 3.

Table 3: Final Carcass Proximate Composition of African Catfish

Component	**T1 (MA)**	**T2 (AU)**	**t**	**p**	**Inference**
Moisture (%)	6.14 ± 2.93	5.64 ± 0.52	0.238	.417	Not significant
Crude protein (%)	62.15 ± 2.76	63.15 ± 0.92	-0.487	.337	Not significant
Crude lipid (%)	16.65 ± 0.21	18.15 ± 0.49	-3.939	.029	Significant
Ash (%)	9.00 ± 0.28	9.75 ± 0.35	-2.343	.072	Not significant
Nitrogen-free extract (%)	6.06 ± 6.18	3.31 ± 0.45	0.628	.297	Not significant
Calculated gross energy (kJ/g)	22.29 ± 0.33	22.64 ± 0.10	-1.465	.140	Not significant

Values are mean ± SD; equal-variances-assumed results are reported at df = 2. NFE (%) = 100 - [moisture + crude protein + crude lipid + ash]. Gross energy was calculated as GE (kJ/g) = [23.6(CP) + 39.5(CL) + 17.2(NFE)]/100 and was not measured by bomb calorimetry. Source: Final carcass analysis and the calculations of the present study.

Table 4: Initial Carcass Composition of African Catfish

Component	**T1 (MA)**	**T2 (AU)**	**Unit**
Crude protein	70.893	75.431	%
Ash	12.020	14.020	%
Moisture	4.330	1.020	%
Crude fat	7.510	6.270	%
Nitrogen-free extract	5.240	3.260	%
Calculated gross energy	20.60	20.84	kJ/g

Values are baseline analytical results and are presented descriptively. Source: Initial carcass analysis of the present study.

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Development and Functionality of the novel SmartAQUA Feeder

The completed prototype combined the feed-dispensing assembly, motor and driver, local controller, temperature input, cellular communication, cloud data handling and mobile application. The system was assigned to T2 and used throughout the 56-day feeding trial.

Mechanical Design and Feed-Dispensing Assembly

The mechanical design consisted of a tapered feed hopper connected to a motor-driven auger and horizontal discharge outlet. The final design visualisation specified a hopper width of 600 mm, an overall height of 540 mm, a base length of 450 mm and a 190 mm discharge section. The front view showed a 400 mm hopper opening and a 300 mm base width. These dimensions defined the intended geometry of the feed-storage and dispensing assembly shown in Figure 8.

Electronic Assembly and Controller Enclosure

The electronic assembly incorporated the ESP32/LTE controller, DM542T motor driver, connection terminals and associated low-voltage wiring. Figure 9 presents the controller and motor-driver assembly housed in the prototype enclosure during the experimental trial.

Device Registration and Mobile Application

The mobile application provided account access and device association before the feeder could be managed remotely. A feeder could be identified by scanning its QR code or by entering the serial number and binding code manually, as shown in Figure 10. After registration, the application provided access to feeding schedules, device monitoring, manual control and feeding records.

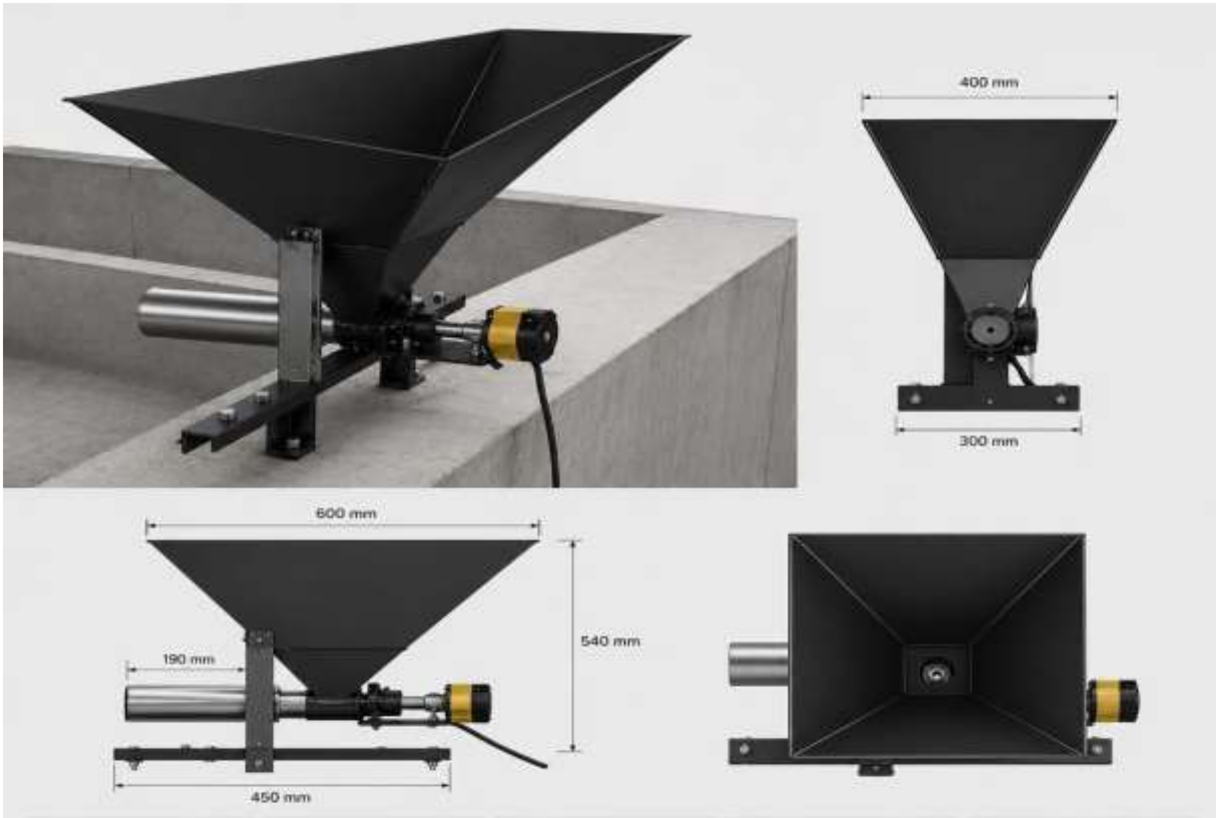

Figure 8: Final Dimensioned Design of the SmartAQUA Feed-Dispensing Assembly

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Figure 9: SmartAQUA Controller and Motor-Driver Assembly Used During the Trial

Figure 10: SmartAQUA Device-Registration Interface

Feeding Schedule and Remote Operation

Two daily feeding events were configured at 09:00 and 17:00. The base daily ration was calculated from the most recently measured live biomass and then divided between the scheduled events. Figure 11 shows both schedules enabled and displayed 129 g for each event at the time the screenshot was captured. The displayed quantity documents that particular schedule setting; it was not treated as a single fixed ration for

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the entire trial because the base ration was updated from the latest biomass measurement.

Figure 11: Active 09:00 and 17:00 Feeding Schedules in the SmartAQUA Application

Temperature Adjustment, Calibration and Trial Use

For T2, the controller applied a temperature-adjustment factor to the biomass-based ration using Q10 = 2.1 and a reference temperature of 25°C. The factor was constrained to the implemented positive range of 0.3 to 2.0. Thermal safety rules limited the ration to 20% below 20°C, reduced it progressively between 32°C and 36°C, and stopped automatic feeding at or above 36°C. The implemented components and settings are summarised in Table 5.

Table 5: Implemented SmartAQUA Functions and Operational Settings

System component or function	**Implemented outcome**
Mechanical assembly	Tapered hopper, auger mechanism and horizontal feed-discharge outlet
Motor and driver	Stepper motor controlled through a DM542T motor driver
Controller	ESP32/LTE controller for schedules, sensing, calculations and motor commands
Temperature sensing	Water temperature supplied as the environmental input to the ration logic
Feeding schedule	Automatic dispensing at 09:00 and 17:00
Biomass ration	Base daily ration set at 3% of the most recent live biomass
Temperature adjustment	Q10 = 2.1 at 25°C, constrained to a positive factor of 0.3 to 2.0

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Thermal safety	20% ration below 20°C, progressive reduction from 32°C to 36°C and feeding stopped at or above 36°C
Feed calibration	10.45 g per auger revolution and 400 effective motor steps per revolution
Communication	Cellular data transfer, MQTT messaging and cloud record handling
Mobile application	Device binding, schedule management, monitoring, manual control and feeding history
Trial use	Smart-assisted feeding applied to T2 throughout the 56-day trial

Source: Implemented SmartAQUA system and experimental records of the present study.

Growth Performance and Somatic Indices

Growth performance and somatic indices are presented in Table 6. Initial weight was 249.35 ± 0.11 g/fish in T1 and 249.45 ± 0.08 g/fish in T2, and the difference was not significant (p = .215). At the end of the trial, T2 recorded a significantly higher final weight of 440.00 ± 4.81 g/fish than the 386.91 ± 2.68 g/fish recorded in T1 (p = .003). T2 also recorded significantly higher weight gain (190.56 ± 4.73 g/fish), average daily gain (3.40 ± 0.08 g/fish/day), specific growth rate (1.013 ± 0.019%/day) and percentage weight gain (76.39 ± 1.88%) than T1, with p = .003 for each comparison. HSI and ISI did not differ significantly between treatments (p = .171 and p = .198, respectively). Survival was 100.00 ± 0.00% in T1 and 96.00 ± 0.00% in T2.

Table 6: Growth Performance and Somatic Indices of African Catfish

Parameter	**T1 (MA)**	**T2 (AU)**	**t**	**p**	**Inference**
Initial weight (g/fish)	249.35 ± 0.11	249.45 ± 0.08	-0.979	.215	Not significant
Final weight (g/fish)	386.91 ± 2.68	440.00 ± 4.81	-13.641	.003	Significant
Weight gain (g/fish)	137.56 ± 2.79	190.56 ± 4.73	-13.644	.003	Significant
Average daily gain (g/fish/day)	2.46 ± 0.05	3.40 ± 0.08	-13.605	.003	Significant
Specific growth rate (%/day)	0.785 ± 0.013	1.013 ± 0.019	-14.012	.003	Significant
Survival rate (%)	100.00 ± 0.00	96.00 ± 0.00	NS	NS	Not significant

Values are mean ± SD. Equal-variances-assumed test results are reported at df = 2. The p values are one-tailed. Negative t-values indicate a higher T2 mean because the test difference was T1 minus T2. Source: Experimental data and IBM SPSS Statistics version 32 output of the present study.

Feed and Nutrient Utilisation Indices

Feed conversion ratio was significantly lower in T2 (2.39 ± 0.06) than in T1 (3.09 ± 0.06; *p* = .004). Conversely, T2 recorded significantly higher feed conversion efficiency (41.85 ± 1.04%) as shown in Table 7.

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Table 7: Feed and Nutrient Utilisation Indices of African Catfish

Index	**T1 (MA)**	**T2 (AU)**	**t**	**p**	**Inference**
Feed conversion ratio	3.09 ± 0.06	2.39 ± 0.06	11.395	.004	Significant
Feed conversion efficiency (%)	32.42 ± 0.66	41.85 ± 1.04	-10.848	.004	Significant

Values are mean ± SD; equal-variances-assumed results are reported at df = 2. A lower feed conversion ratio indicates better feed use, whereas higher values indicate better performance for the other indices. Source: Experimental data and IBM SPSS Statistics version 32 output of the present study.

Cost-Effectiveness of the systems

The confirmed feed price was ₦26,000 per 15-kg bag, equivalent to ₦1,733.33/kg. Manual feeding required an average of 4 minutes per feeding event, while SmartAQUA required approximately 5 seconds per feeding event. With two sessions daily across 48 feeding days, manual feeding totalled 6.40 labour-hours and SmartAQUA totalled 0.13 labour-hours (8 minutes). The resulting reduction in labour time and imputed labour cost was 97.92%. SmartAQUA produced an additional 0.755 kg of biomass gain at an additional operating cost of ₦244.58, giving an incremental operating cost of ₦323.91 per additional kilogram gained. The recorded prototype investment was ₦278,000, comprising ₦240,000 for construction, fabrication and installation and ₦38,000 in additional capital/component expenditure. This investment was reported separately from the 56-day operating-cost comparison.

The relevant information is presented in Table 8.

Table 8: Cost-Effectiveness Comparison Between Manual Feeding and SmartAQUA

Cost indicator	**Manual**	**SmartAQUA**	**Difference**
Feed cost	₦18,387.56	₦18,941.12	+₦553.56
Labour time	6.40 h	0.13 h	-6.27 h
Labour cost	₦2,153.85	₦44.87	-₦2,108.97
Communication cost	₦0.00	₦1,800.00	+₦1,800.00
Total relevant cost	₦20,541.41	₦20,785.99	+₦244.58
Feed incidence cost (₦/kg biomass gain)	₦5,271.01	₦4,463.54	-₦807.47
Total relevant cost/kg biomass gain	₦5,888.44	₦4,898.29	-₦990.15
Cost/surviving fish	₦821.66	₦866.08	+₦44.43

DISCUSSION

Water Quality Parameters

None of the four measured water-quality variables differed significantly between T1 and T2. Conductivity, pH, dissolved oxygen and temperature were therefore statistically comparable on the four monitoring occasions and were within the acceptable range for the culture of African catfish. An imbalance between treatment tanks would therefore weaken the interpretation of a feeding-system comparison (Ogunji and Wuertz, 2023). The water-quality results support a more direct comparison of the two feeding methods under the measured culture conditions. They also reduce the likelihood that the observed growth pattern was explained by a large difference in the monitored water quality parameters (Mundim *et al.*, 2020; Percie du Sert *et al.*, 2020).

Development and Functionality of the Novel SmartAQUA Feeder

The development and trial use of an integrated feeder that combined mechanical dispensing, electronic control, temperature-responsive rationing, communication and user access was achieved in this study. Akhter *et al.* (2021) and Ubina *et al.* (2023) similarly described sensing, communication and decision support as the principal layers of connected aquaculture systems.

The tapered hopper, auger and discharge outlet formed a direct mechanical path from stored pellets to the culture unit.

The ESP32/LTE controller and DM542T driver connected the software decision to the dispensing mechanism. The controller handled schedules, sensing, ration calculations and communication, while the motor driver supplied the step sequence used to rotate the auger. This local-control layer is important because an automated aquaculture device must execute the feeding event at the equipment even when monitoring and data storage are provided remotely (Ubina *et al.*, 2023; Yang *et al.*, 2021).

The device-registration interface strengthened operational control by requiring the feeder to be associated with a user account through QR scanning or manual entry of its serial number and binding code. Once registered, the mobile application provided schedule management, monitoring, manual commands and feeding history. The application therefore acted as the user-facing layer of the sensing, communication and actuation chain (Akhter *et al.*, 2021; Yang *et al.*, 2021).

Temperature adjustment added an environmental response to the biomass-based ration. The Q10 factor modified the calculated quantity around the 25°C reference, while the imposed factor limits and high-temperature cut-off prevented unbounded feed commands. Such control logic is useful because fish feeding activity and metabolic demand vary with temperature, although the specific thresholds still require validation for the target production setting (Kasihmuddin *et al.*, 2021; Mundim *et al.*, 2020).

Using the system for the full feeding trial demonstrated functional integration of the implemented modules under the study conditions. However, the present objective evaluated development and trial operation rather than long-term commercial reliability. Longer-duration tests should quantify dispensing error, missed-event frequency, communication downtime, battery performance and resistance to feed bridging before the prototype is described as production-ready (Akhter *et al.*, 2021; Ubina *et al.*, 2023).

Fish Carcass Composition

The initial carcass analysis therefore established the treatment-specific composition before manual and SmartAQUA feeding began. These values provide the baseline against which final protein, lipid and energy content will be assessed (AOAC, 2023). Final crude lipid was significantly higher in T2, 18.15 ± 0.49%, than in T1, 16.65 ± 0.21% ($p = .029$). Phan *et al.* (2022) reported that lipid deposition makes an important contribution to retained body energy in African catfish. The higher T2 lipid content is consistent with the higher lipid efficiency ratio and apparent lipid retention recorded under SmartAQUA feeding, indicating greater apparent deposition of dietary lipid in the fish carcass (Langi *et al.*, 2024). The significantly higher final crude lipid in T2 indicates greater lipid deposition under SmartAQUA feeding, whereas final crude protein and calculated gross energy did not differ significantly between treatments were corroborated by findings from Karp *et al.*, (2021) and Percie du Sert *et al.*, (2020) that fish generally improved on their initial carcass when given a balanced ration.

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Growth Performance and Somatic Indices

The treatments began at closely comparable mean weights, 249.35 g/fish in T1 and 249.45 g/fish in T2, and the difference was not significant. Weight gain was 190.56 g/fish in T2 compared with 137.56 g/fish in T1, and average daily gain was 3.40 compared with 2.46 g/fish/day. Both differences were significant at p = .003. Langi *et al.* (2024) noted that feeding conditions affect the rate at which African catfish convert dietary supply into biomass. In the present study, the agreement between cumulative weight gain and daily gain shows that the advantage was sustained across the feeding period rather than being restricted to a single measurement (Dauda *et al.*, 2022).

Specific growth rate was 1.013%/day in T2 and 0.785%/day in T1, while percentage weight gain was 76.39% and 55.18%, respectively. The observed growth advantage may be associated with the combined effects of fixed feeding times, calibrated dispensing, biomass-based ration updates and temperature adjustment.

Indriastuti *et al.* (2022) showed that feeding conditions and timing can alter the opportunity for fish to obtain feed, while Kasihmuddin *et al.* (2021) demonstrated the biological relevance of temperature to African catfish performance. The contribution of each individual function cannot be separated from the present because the experiment tested these functions as one integrated strategy. (Dauda *et al.*, 2022). The final weight, weight gain, average daily gain, specific growth rate and percentage weight gain consistently showed better growth under SmartAQUA in this trial.

Feed and Nutrient Utilisation Indices

Feed conversion ratio was significantly lower in T2, 2.39 ± 0.06, than in T1, 3.09 ± 0.06 (p = .004), whereas feed conversion efficiency was significantly higher in T2, 41.85 ± 1.04%, than in T1, 32.42 ± 0.66% (p = .004). The simultaneous reduction in FCR and increase in FCE indicate that the smart-assisted treatment produced more fish biomass from each unit of recorded feed supplied. Calibrated automatic dispensing can improve the regularity and repeatability of ration delivery (Thornburg, 2025; Shaw *et al.*, 2022).

In the current study, the feed and nutrient utilisation results show that SmartAQUA feeding improved feed conversion ratio, conversion efficiency, protein efficiency ratio, lipid efficiency ratio, apparent lipid retention and gross-energy retention. Apparent net protein utilisation and productive protein value were numerically higher in T2 but were not significantly different. The agreement between the growth and feed-use indices indicates that the higher biomass produced in T2 was accompanied by more efficient use of the recorded feed supply under the conditions of the eight-week trial (Langi *et al.*, 2024; Thornburg, 2025).

Labour Saving, Cost-Effectiveness and Nutrient Economics

Reducing feeding-execution time from 4 minutes per manual event to approximately 5 seconds per SmartAQUA event produced a 97.92% reduction in the time assigned to routine feed delivery. The reduction is important because feeding is repeated daily and competes with water management, grading and record keeping for farm labour (Food and Agriculture Organization of the United Nations, 2013; Olagunju *et al.*, 2024).

Total relevant operating cost was ₦20,541.41 under manual feeding and ₦20,785.99 under SmartAQUA. Despite the slightly higher total operating expenditure, SmartAQUA produced more biomass and had a lower operating cost per kilogram of biomass gain: ₦4,898.29 compared with ₦5,888.44 under manual feeding. The additional 0.755 kg of biomass gain required ₦244.58 of additional operating expenditure, equivalent to ₦323.91 per additional kilogram gained (Olagunju *et al.*, 2022; Olagunju *et al.*, 2024).

CONCLUSION

This study evaluated the effect of a novel smart-assisted automatic feeder on the growth performance and cost-effectiveness of African catfish, *Clarias gariepinus*, during an eight-week feeding trial. The measured water-quality parameters remained comparable between the manual and SmartAQUA treatments, while the same commercial feed was supplied to both groups. The SmartAQUA feeder combined biomass-based ration calculation, scheduled feeding, real-time water-temperature adjustment, calibrated auger dispensing, cellular communication and mobile monitoring.

The novel SmartAQUA produced a lower operating cost per kilogram of biomass gain and achieved additional biomass at an incremental operating cost of ₦323.91 per additional kilogram. It is therefore concluded that the prototype improved feed-management efficiency, feeding-time compliance, labour efficiency and cost-effectiveness under the conditions of this study. Furthermore, the current study showed that SmartAQUA improved growth and the system reduced dependence on manual rationing. The novel SmartAQUA therefore showed promise for African catfish culture.

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