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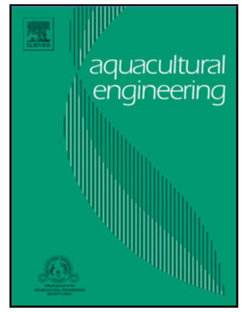

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Improving feeding strategies for shrimp farming using fuzzy logic, based on water quality parameters.

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Abstract

In intensive shrimp farming systems, formulated feed represents the main nutrition source and its adequate management significantly influences the economic feasibility of the farm. Based on that, the present study evaluated two dynamic feeding strategies: fuzzy logic (FL) and mathematical functions (MF). For both strategies, the temperature and dissolved oxygen were modified in a controlled way. A conventional feeding table was the control treatment. The results showed that DO was the parameter that mostly influences the feeding rate (74%)

while the temperature also did it, but in a lower grade (26%). The results showed that feed conversion rate (FCR) was significantly better when the FL strategy was used, saving around 35 % of feed when compared to the control. An expert system based on FL may replace the traditional feeding strategies with no significant adverse effects on growth, survival and FCR, and may easily be adapted to some other culture systems.

Key words: fuzzy logic, *Litopenaeus vannamei*, feeding, aquaculture, water quality.

Introduction

In intensive shrimp farming, the nutrition of the cultured organisms depends strongly on the formulated feed supply (Tacon et al., 2011). The challenge of intensified aquaculture is to maximize the feeding efficiency and at the same time take care on the health of the culture system and the environment around (Nunes and Parsons, 2006). Up to day, most farmers fed shrimp based on conventional tables, which consider the size and biomass of the organisms to adjust the feeding rate. Another practice is the use of feeding trays in which the rate is adjusted accordingly to the apparent feed consumption (Casillas-Hernández et al., 2007; Martinez-Cordova et al., 1998; Smith et al., 2002). Most recently, the investigations suggest that a better strategy must consider the real consumption and assimilation of feed, depending on the environmental conditions.

The water quality (mainly temperature and dissolved oxygen) directly influence the consumption and assimilation of feed (Martínez-Córdova et al., 2013). At present, some tools have been developed to help farmers on the decision making on the feeding of farmed organisms and on the simulation of the effect of environmental parameters on it (Leo et al., 2016; Nunes and Parsons, 2006; Wu et al., 2015). The term “fuzzy logic” was introduced by Lotfi Asker Zadeh in 1965 as a way to approach the “common sense” problems, using “in” and “after”. From that, many investigations have boarded problems using fuzzy logic. (Carbajal_Hernandez et al, 2013) The fuzzy logic has been probed in recirculating aquaculture systems for the evaluation of water quality, and on the supply of feed in the culture of tilapia (*Oreochromis aureus*), silver perch (*Bidyanus bidyanus*), and trout (Carbajal-Hernández et al., 2012; Lermontov et al., 2009; Soto-Zarazúa et al., 2010a, 2010b; Wu et al., 2015; Yalcuk and Postalcioglu, 2015). However, this tool has not been used to predict the feed consumption in shrimp aquaculture.

The present study was designed to assess two feeding strategies to predict the feed consumption in an intensive shrimp culture: fuzzy logic (FL) and mathematical functions (MF) based on changes of temperature and dissolved oxygen, using a conventional feeding table as a control.

Materials and Methods

The study was conducted in the facilities of Aquaculture Laboratory of the Instituto Tecnológico de Sonora, sited at Ciudad Obregon, Sonora, México. Two experimental trials were done: the first to evaluate the effect of temperature and dissolved oxygen on the apparent consumption of feed by *L. vannamei*, and the second to assess two feeding strategies of dynamic feeding: fuzzy logic and mathematical functions, as compared to a static feeding strategy (feeding tables).

The experimental organisms (shrimp with a mean weight of 0.96 ± 0.34 g) acquired from a commercial laboratory (Biomarina S.A. de C.V.), were stocked in 12 plastic tanks of 10 liters each at a density rate of 0.5 PL/L. Commercial formulated feed (Camaronina-35, Purina de México S.A. de C.V.) composed of 88% of dry matter, 8% of lipids and 35% of protein was used. Shrimp were fed twice a day for 7 days at a rate of 20% of shrimp biomass per day. The feed was offered in excess to estimate in a better way the consumption.

Effect of temperature:

Four treatments by quadruplicate were evaluated by maintaining 4 controlled temperatures in aisled rooms (22±0.21, 26±0.54, 30±0.61 and 34±0.43°C) at a constant dissolved oxygen (DO) concentration of 5±0.32 mg/L. Air conditioning units with temperature control were used for the treatments 22°C and 26°C. Environment heaters controlled by thermostats, were utilized for the treatments 30°C and 34°C. In both cases, the controllers were revised every 6 hours.

Effect of dissolved oxygen:

Three treatments were evaluated by triplicate to assess the effect of DO, supplying the gas in a controlled manner by using regulating valves to maintain concentration of: 1-2 mg/L, 3-4 mg/L, and 5-6 mg/L, at a constant temperature of 28±0.36 °C. Juvenile shrimps with a mean weight of 1.15±0.14g were stocked in nine plastic tanks of 10 liters each (0.5 juvenile/L). They were fed a commercial shrimp diet (PURINA 35% of crude protein), twice a day at a rate of 20% of their biomass per day, during 7 days with zero water exchange.

Apparent feed consumption:

The apparent feed consumption was calculated by the formula (equation 1) suggested by Sick et al. (1973) as:

$$Ac(\%) = \frac{Fs-Fuc}{Fs}\ x\ 100 \qquad \text{Equation 1}$$

Where Ac was the apparent consumption, Fs was the supplied feed, and Fuc was the unconsumed feed.

Evaluation of dynamic feeding strategies:

Juvenile shrimp (1.69±0.24g) were stocked in fiberglass tanks (100 L) at a density of 15 shrimp/tank (0.15 shrimp/L) with a water exchange around 8 – 10 % per day.

Shrimp were fed a commercial feedstuff with 35% CP, supplied three times a day (0800h, 1300h y 1800h). Feeding trials were used as a control, adjusting the daily ration according to apparent consumption.

Temperature and DO were monitored twice a day (1000h and 1700h) by means of a portable equipment YSI 55.

A. Fuzzy logic:

Entries of the system

The range of temperature was 18 to 34 °C, as typical values found in commercial shrimp farms of northwester Mexico (Casillas-Hernandez et al., 2006). For DO the range considered was 0 to 20 mg/L, which are values possible to be recorded in regional shrimp farms (Martinez-Cordova, 1998; Paez-Osuna and Valencia-Castañeda, 2013)

Fuzzification

The fuzzification was constructed using triangular functions accordingly to the methodology suggested by Kusko (1993). For the automatic feeder, the entry values were converted to functions of pertinence (μ; values among 0 and 1), by means of the triangular way as shown in Figures 2 and 3. The logic operators were: union (OR); interaction AND); and negation (NOT) (Rajak et al. 2016; Vadiati et al. 2016). For this particular case the function AND was applied, as shown in equation 2.

Interaction (AND) $\mu_{A\cap B}(x) = \min\{\mu_A(x), \mu_B(x)\}$ Equation 2.

Fuzzy rule-base

The base of the fuzzy rules were established accordingly to the methodology of Ross (2012). For this particular study 25 rules were performed as shown in Table 1.

Inference process

The inference process was established considering the studies od Valdiati et al. (2016) and Tamilselvan and Aarthy. (2017). For the present study the entry variables of water quality were used to produce an exit variable (feed rate) (Figure 1).

Defuzzification interface

For defuzification, the center of gravity method was used as shown in equation 3, accordingly to the methodology of Passino and Yurkovich (1998) and Soto-Zarazua et al. (2010).

$$\mu^* = \frac{\sum_i xi \int \mu(i)dx}{\sum_i \int \mu(x)dx} \quad \text{Equation 3}$$

Where $u*$ is the exit response on percent of feed from the fuzzy system; xi indicates the center of a triangular fuzzy set (VLFR, LFR, NFR, HFR and VHFR) and $\int \mu(u(i))$ represents the sum of the areas in the truncated triangles of the exit fuzzy set.

$$\mu\big(u(i)\big) = w_i \left(h_i - \frac{{h_i}^2}{2}\right) \quad \text{Equation 4}$$

where w_i is the base value of the output fuzzy set and h_i is the height where each fuzzy set is truncated horizontally (equation 4).

B. Mathematical functions (MF):

Mathematical functions were used to calculate de percent of food to supply. The mathematical functions were determined according to the software MATLAB by the use of the toolbox curve fitting (The MathWorks, 2012). The curves that fitted better to the comportment observed in probes done with temperature and dissolved oxygen, were selected. The selection criteria were based on: the determination coefficient (r^2), the square sums of the error (SSE), and quadratic medium error (RMSE) (Li et al., 2016).

C. Control treatment (CT):

The feeding rate in CT was based on a feeding table (Martinez-Cordova et al. 2013), which suggest that shrimp from 0.5 to 3 g, must be fed at a rate of 6 %; from 3 to 5 g, at 5 %; from 5 to 10 g, at 4 % and more than 10 g at 3 %.

To determine significant differences among treatments, a one-way ANOVA was performed, at a 95 % of confidence by means the statistical Sigmaplot version 12.0 for Windows.

Results

Table 2 presents the effect of temperature on feed consumption. It is clear that the consumption increased as temperature did it. At 22 °C, shrimp consumed around 44.19% of the feed supplied, while at 30 °C the consumption increased 29.81%, which suggest that the optimal temperature range for shrimp culture could be 28 to 30 °C. This umbral was taken as reference. At 34°C, the consumption was 92.18%, corresponding to an increase of 18.18%, while at 26 °C, the consumption was 62.44%, a decrease of 11.56%.

Table 3 shows the effect of dissolved oxygen on the feed consumption. Into the optimal umbral, the consumption was 60.11 %. When DO decreased at 2 mg/L, the consumption decreased at 24.81 %; when DO decreased at 1 mg/L, the consumption decreased at 13.28%. Over the levels evaluated, the consumption remains stable.

As shown in Fig. 4 A, feed consumption (FC) increased as temperature did. Based on that tendency, a first order polynomial equation can describe mathematically the comportment of feed consumption in function of temperature.

In this case, the comportment is sigmoidal, and it was observed that at a level ≥ 5 mg OD/L, the consumption stabilizes. Equations 5 (temperature) and 6 (DO) are mathematical functions describing the effect of these parameters on FC, where the % of feed was supplied according shrimp biomass. Table 4 shows the statistical characteristics for both mathematical functions with an $r^2 > 0.99$ and a SSE < 0.2, which permits and adequate adjustment to calculate the effects in real time during the trial.

$$\% \, Feed = \frac{(5.264 * T + 0.001642)}{(T + 0.4333)} \quad \text{Equation 5}$$

$$\% \, Feed = 0.1944 * \mathrm{OD} - 0.7346 \quad \text{Equation 6}$$

Fig. 5 shows a simulation of the controller of fuzzy logic which evidences to the system the relationship with the two variables and their effect on FC, this was obtained by using the Fuzzy Logic Control ToolBox from the commercial software MATLAB R2013a. During the trial, temperature recorded high picks (33.20 ± 0.51 °C), medium picks (29.01 ± 0.41), and low peaks (22.91 ± 1.33 °C). Similarly, DO recorded high concentrations (8.31 ± 3.19 mg/L) and medium concentrations (5.82 ± 2.83).

The static feeding rate (control treatment) was 5 % of shrimp biomass at the beginning of the trial; when shrimp reached 5 g, the rate was reduced to 4 %. In that case, the effects of temperature and DO where not considered (Fig. 6).

In treatment MF (Fig. 7) the feeding rate was adjusted as follow: at high temperature the rate was 5.23 ± 0.16%; at medium temperature, it was 4.89 ± 0.11 and at low temperature it was 3.44 ± 0.13.

In treatment FL (Fig. 8), the feeding rate was adjusted in the follow manner: At high temperatures the rate was 5.13±1.41; at medium temperature, 4.64 ± 0.95; and at low temperature, 2.19 ± 0.85. Both treatments showed a similar trend to those observed in the individual probe done for temperature, with a decrease of feeding rate when temperature decreased. When a decrease in DO occurred, the feeding percentage (FP) also decreased abruptly so it is evident that treatment FL exhibited a higher sensibility to DO changes, as indicated by the SD values. Treatment MF did not record significantly adjustments on FC when environmental variables changed abruptly, as compared to treatment FL, when DO decreased abruptly, in which case it showed the best adjustments and adaptation to real time conditions of the culture.

Shrimp production parameters and feed consumption during the trial are shown in Table 5. The lowest feeding rate was observed in treatment FL with 2.51%, followed by MF with 2.79%, and finally the control with 4.61%. The percentage of consumed feed was 69.63% for FL treatment, 57.27% for MF, and 51.34% for the control, which suggest the feed was more efficiently supplied in treatment LF. Under normal conditions of dissolved oxygen (> 5 mg/L) the feeding rate for LF was 4.28%, for MF, 4.59%, and for the control, 4.60%. The greatest consumption was observed in FL with 88.43%, followed by MF with 81.10%, and the control with 77.29%. The higher growth rate was obtained in FL (0.59g/week), followed by MF (0.54g/week), and the control (0.52g/week), however no significant differences were detected among treatments. The final survival in the control was 93.33%, while in MF and LF was 91.11%. The lowest feed conversion rate was obtained in FL (1.95), followed by MF (2.56) and the control (3.01). The difference between FL and the control corresponded to 35.21%.

Discussion

At present, diverse strategies have been used to adjust feed supply in commercial farms or at experimental level. Martinez–Cordova et al. (2013) mention some of these strategies based on size, biomass, natural productivity, environmental conditions, among other. Casillas-Hernández et al. (2006) suggest that feeding trays is a better practice as compared to the traditional feeding tables. All of the above mentioned are static feeding practices, but most of the culture systems at present, are dynamic. It has been demonstrated that changes on the environmental variables or in the water quality affect the ingestion and assimilation of the supplied feed. Temperature and dissolved oxygen are the main environmental parameters affecting shrimp feeding (Ayisi et al., 2017; Jørgensen et al., 2017; Ouellet et al., 2017; Ponce-Palafox et al., 1997; Wyban et al., 1995), which suggest that the design and use of dynamic feeding strategies based on changing the feed supply accordingly to the changes of those parameters in real time, could result beneficial on the productive response of the farmed organisms. The results of our study agree with those reported by Carbajal-Hernandez et al (2013) who proposed a water quality index assigning a priority level to each water parameter through a new analytical hierarchical process (AHP), and found that dissolved oxygen and temperature were two of the most important parameters influencing the water quality.

In the present study, the FCR was lower using the dynamic feeding systems, being the fuzzy logic the best strategy with a value of 1.92. The mathematical functions also was good with a value of 2.56. Both values are into the range managed as suitable in commercial farms. The FCR obtained in the control was 35.21% higher than those recorded in the treatment FL.

In the state of Sonora, Mexico, the shrimp production in 2015 was around 60,000 MT managing a mean FCR of 1.8 (COSAES, 2014); according to these data, the feed supplied was around 180,600 MT with a price of $1250.00 USD/MT, which correspond to an expense of $131, 625,000.00 USD. If the FL was applied, a saving of $41,175,000.00 USD could be obtained.

In the other hand, a reduction of 35 % on the formulated feed supply, can contribute to diminish the environmental impact of shrimp farm discharges. Tacon, (2002) and Martínez-Córdova et al. (2009), documented that in the production of one TM of shrimp managing a FCR of 1.0, 500 kg of organic matter (OM), 26 kg of nitrogen (N) and y 13 kg of phosphorous (P) are discharged in the effluents. However, if the FCA is 2.5 (as happen in many farms of Mexico and worldwide), 1625 kg of OM, 117 of N and 38 of P for each MT produced. In the present study, for the control treatment the production of MO was 2008 kg, N, 148 kg and P, 46 kg for each MT of shrimp. In the treatment FL, the organic matter produced was 1213 kg, N, 84 kg, and P, 28 kg (Table 6). Considering these data to the 60,000 MT produced in Sonora, México during 2015, using the feeding strategy of FL, the reduction of organic matter would be 47,700 MT, for N would be 3866 MT and for P, 1,042 MT.

Conclusions

The dynamic feeding strategies evaluated in the present study (fuzzy logic and mathematical functions) showed to be more adequate in adjusting the feeding rate as compared to the static (traditional) strategy. The main benefit was the savings in the use of feed, without a negative effect on growth and survival of shrimp, and the reduction of organic matter, nitrogen and phosphorous discharged. This was because both dynamic strategies consider the changes on the main environmental parameters to adjust the feed supply to the real demand of the farmed organisms. Based on the FCR, consumed feed, productive response and water quality, the best treatment was that based on fuzzy logic.

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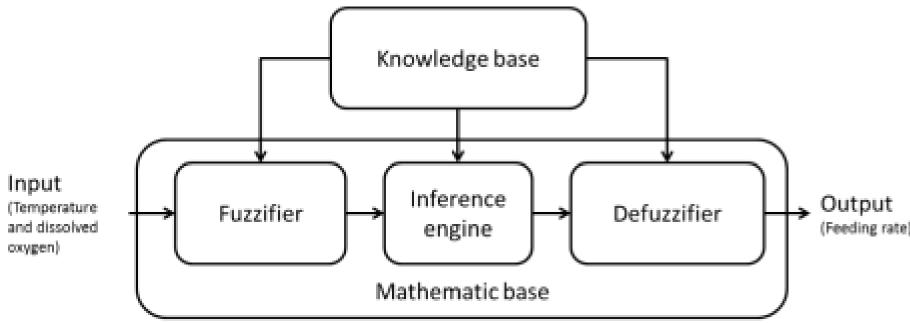

Fig. 1. Scheme of fuzzy system: Temperature and dissolved oxygen are the inputs measured that enters to the fuzzifier block. The feeding rate is the output we get from the defuzzifier block once the inputs passed through the inference engine and were assigned a rule from the knowledge base.

$$\mu(x) = \begin{cases} 0 & \text{for } x \le a \\ \frac{x-a}{m-a} & \text{for } a < x \le m \\ \frac{b-x}{b-m} & \text{for } m \le x \le b \\ 0 & \text{for } x > b \end{cases}$$

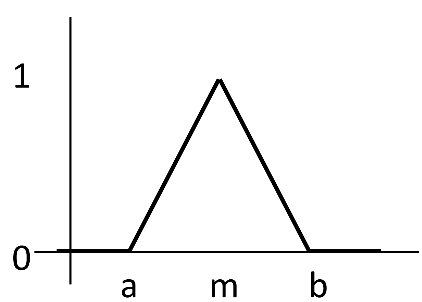

Fig. 2. Transference functions for a triangular fuzzy system, where x is the entry variable; a, b and m, are the pertinence functions.

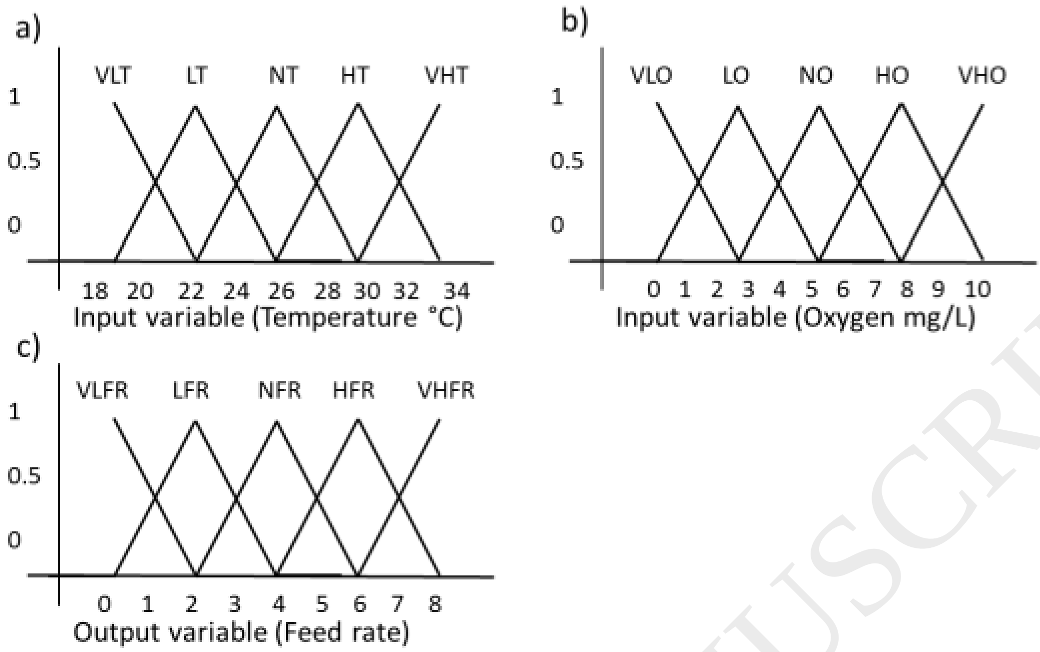

Fig. 3. a) Entry fuzzy variables for temperature (°C) and **b)** for dissolved oxygen (mg/L); **c)** exit fuzzy variables for feeding rate as biomass percentage.

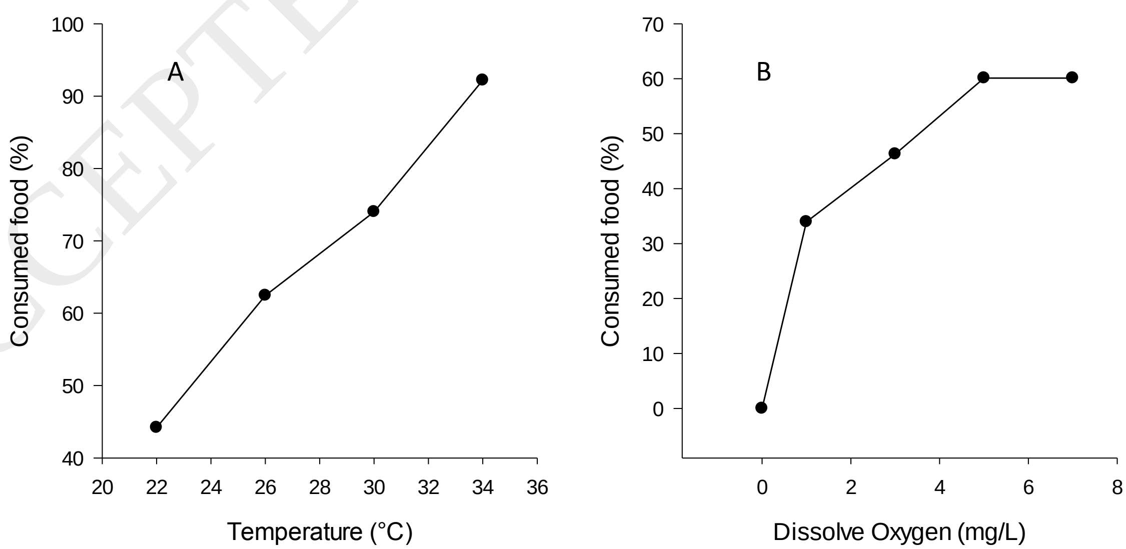

Fig. 4. A) Behavior of feed consumption in function of temperature at ≥ 5 mg OD/L; B) behavior of feed consumption in function of DO at 28±0.36 °C.

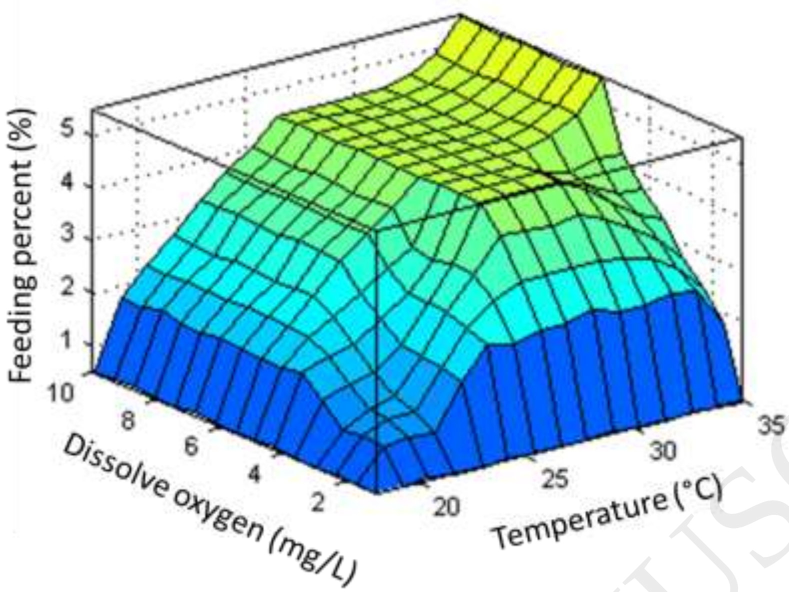

Fig. 5. Simulation result of fuzzy controller with complete operation range of temperature (18 – 35°C) , dissolved oxygen (0 – 10 mg/L) and feeding percent (%) of shrimp body weight.

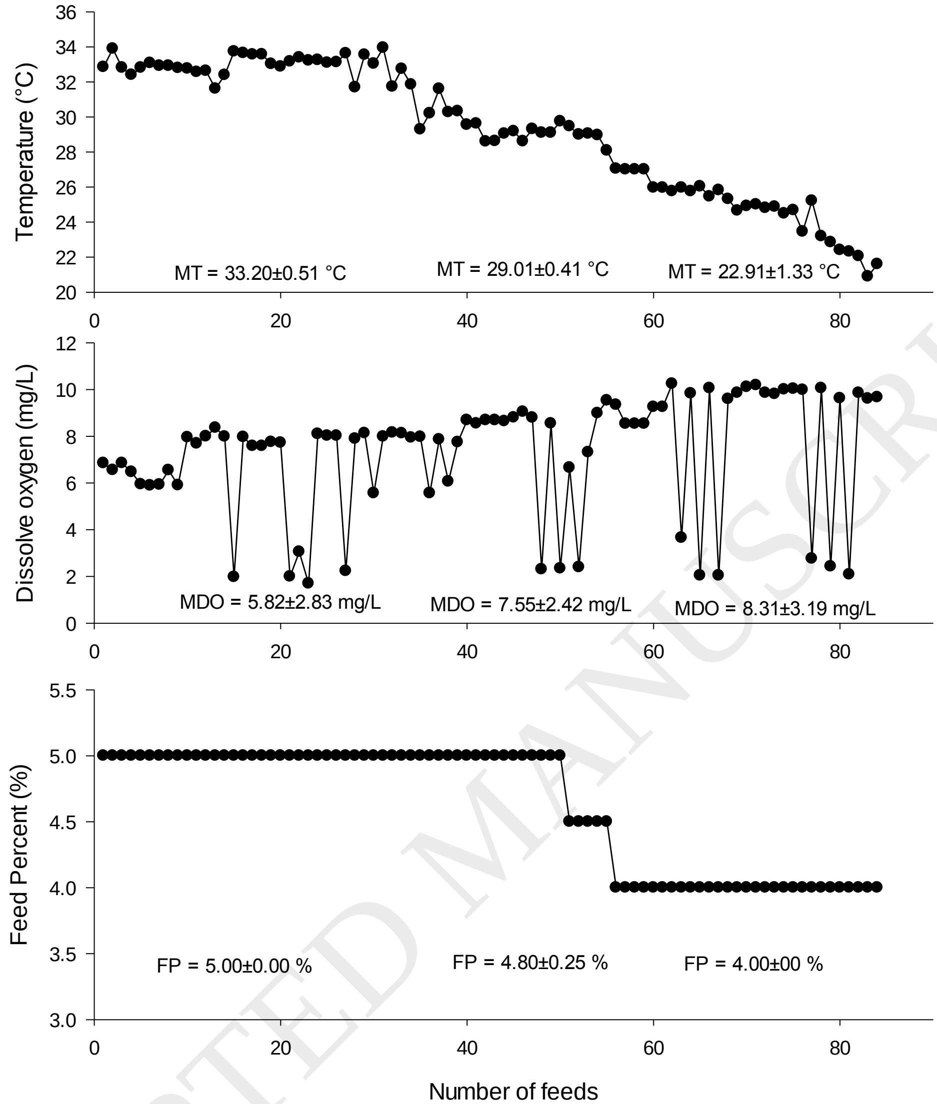

Fig. 6. Comportment of temperature (°C), dissolved oxygen (mg/L) and static feeding rate (% biomass). MT: Mean temperature, MDO: Mean dissolved oxygen and FP: feeding percent.

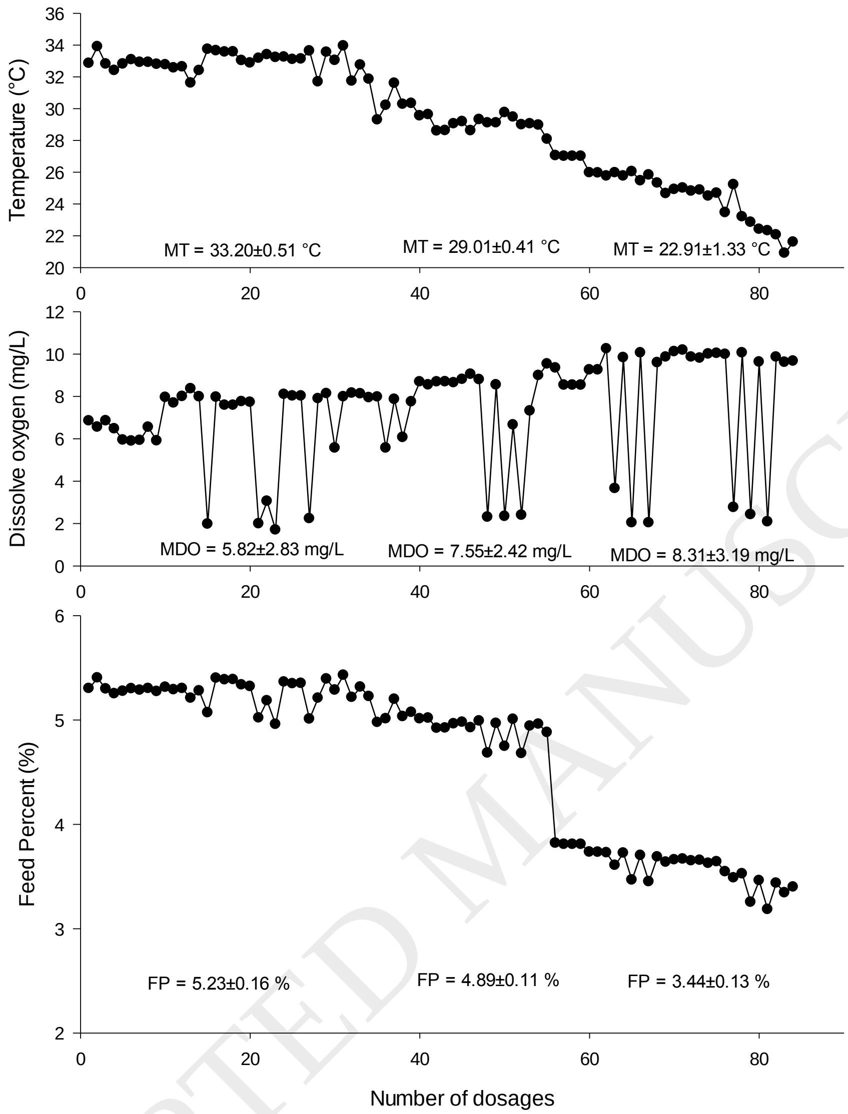

Fig. 7. Comportment of temperature (°C), dissolved oxygen (mg/L) and feeding rate (% of biomass) using mathematical functions. MT: Mean temperature, MDO: Mean dissolved oxygen and FP: feeding percent.

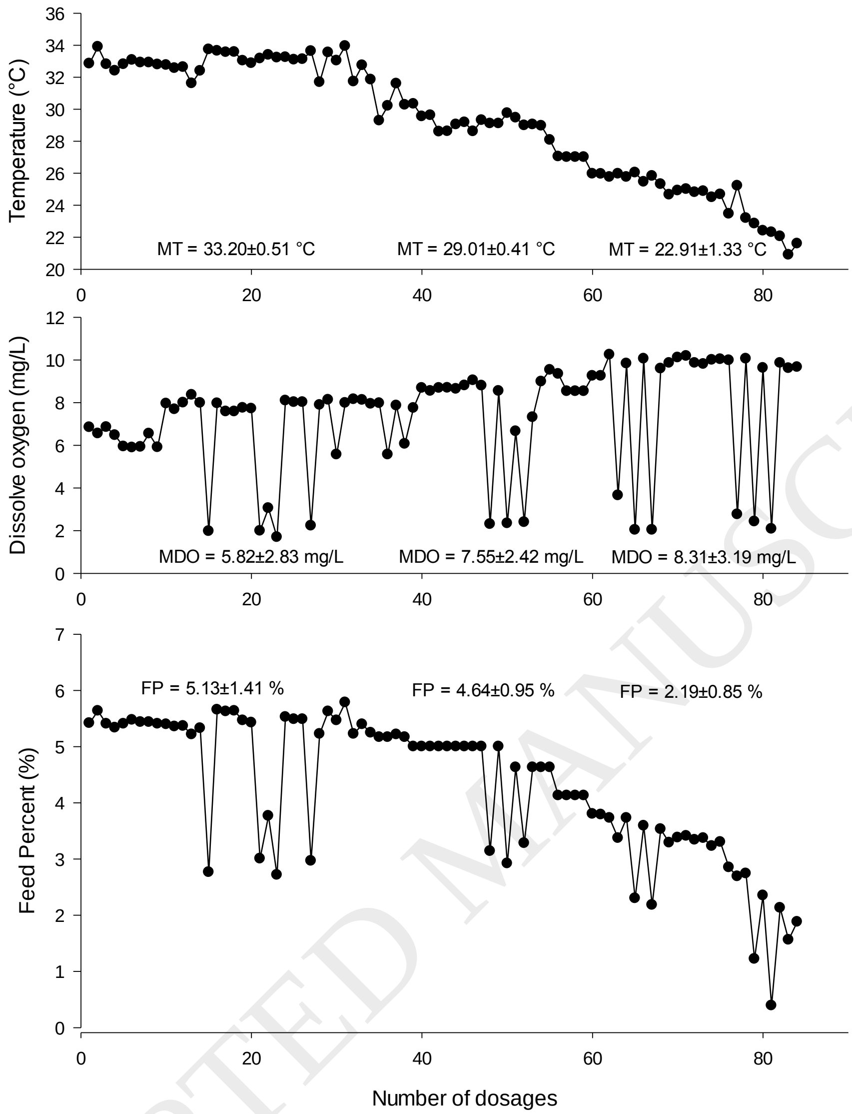

Fig. 8. Comportment of temperature (°C), dissolved oxygen (mg/L) and dynamic feeding rate (% biomass), using fuzzy logic. MT: Mean temperature, MDO: Mean dissolved oxygen and FP: feed percent.

Table 1

Linguistic values to obtain the base rules for temperature (°C), dissolved oxygen (mg/L), and feeding percentage

Temp/OD	VLO	LO	NO	HO	VHO
VLT	VLFR	VLFR	VLFR	VLFR	VLFR
LT	VLFR	LFR	NFR	NFR	NFR
NT	VLFR	HFR	HFR	HFR	HFR
HT	VLFR	HFR	HFR	HFR	HFR
VHT	VLFR	HFR	VHFR	VHFR	VHFR

Fuzzy rules used: very low oxygen (VLO), low oxygen (LO), normal oxygen (NO), high oxygen (HO), very high oxygen (VHO), very low temperature (VLT), low temperature (LT), normal temperature (NT), high temperature (HT), very high temperature (VHT), very low feeding rate (VLFR), low feeding rate (LFR), normal feeding rate (NFR), high feeding rate (HFR) and very high feeding rate (VHFR).

Table 2

Effect of temperature on food consumption (%) and the difference between them considering 30 °C as the reference point.

Temperature (°C)	% of consumed feed	Difference (%)
22	44.19	-29.81
26	62.44	-11.56
30	74.00	---
34	92.18	+18.18

Table 3.

Effect of dissolved oxygen on food consumption (%) and the difference between them considering 5- 6 mg/L as the reference point.

Dissolved oxygen (mg/L)	Consumed feed (%)	Difference (%)
0	0	---
1 - 2	33.96	-26.15
3 - 4	46.29	-13.28
5 - 6	60.11	---

Table 4

Statistical results of mathematical functions obtained from behavior of feed consumption for temperature and dissolved oxygen.

	Equation 4	Equation 5
r^2	0.994	0.9927
SSE	0.104 % of feed	0.0221 % of feed
RMSE	0.228 % of feed	0.1053 % of feed

Table 5.

Means (± SD) of the productive parameters on the shrimp in the treatments and control. LO = Low oxygen; NO = Normal oxygen.

	Parameter	Treatment		
		FL	MF	Control
LO	Feeding rate (%BW)	2.51[a]	2.79[ab]	4.61[b]
	Consumed feed (%)	69.63[a]	57.27[a]	51.34[a]
NO	Feeding rate (%BW)	4.28[a]	4.59[a]	4.60[a]
	Consumed feed (%)	88.43[a]	81.10[a]	77.29[a]
	Growth rate (g)	0.59[a]	0.54[a]	0.52[a]
	Survival (%)	91.11[a]	91.11[a]	93.33[a]
	FCR	1.95[a]	2.56[ab]	3.01[b]

Table 6.

Amounts of organic matter (OM), nitrogen (N), and phosphorous (P) discharged by each MT of shrimp produced

Treatment	FCR	OM (kg)	N (kg)	P (kg)
Control	3.01	2008	148	46
Mathematical functions	2.56	1670	121	38
Fuzzy logic	1.95	1213	84	28