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Proposal and assessment of an aquaculture recirculation system for trout fed with harvested rainwater

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ABSTRACT

A sustainable aquaculture production involves alternatives, as recirculating aquaculture systems (RAS), in order to increase the water supply efficiency. This paper aims: a) to propose a method for dimensioning a RAS filled and additionally supplied with water from a rainwater harvesting systems (RHS) and; b) to evaluate the efficiency of the system based on the supply of rainwater from the RHS, the quality of water in the RAS, and the development of aquatic organisms. A pilot aquaculture farm for rainbow trout (Oncorhynchus mykiss) production was designed and dimensioned. On one hand, the RAS with a configuration based on a treatment tower provided acceptable values of pH, TAN, and alkalinity. The temperature was slightly above the recommended temperature but did not negatively impact trout development. On the other hand, the water use efficiency reached 178 L/kg of fish, instead of 210,000 L/kg in an open flow system for trout rearing. The RHS fulfilled the additional required water on the test period of the pilot farm and is expected to supply at least 92% on average during the useful life. Regarding the aquatic organisms' development, the system allowed both a better Length/weight ratio and a lesser mortality rate compared to previous studies of RAS. In contrast to other studies in the literature, the mathematical models for dimensioning the system were calculated as a function of the final biomass expected in the tank instead of the quantity of supplied feed. Therefore, this method confirmed the applicability of this alternative criterion for designing biofilters and aquaculture systems.

1. Introduction

Sixty percent of the water requirements of global aquaculture production is supplied by freshwater sources (Subasinghe, 2017). Besides the well-known studies about aquaculture open systems, groundwater contributes with a significant portion of this freshwater requirement in several regions around the world. In fact, in The United States, nearly 20% of water resources destined to aquaculture originates from aquifers (Maupin et al., 2014). In Armenia, at least one-third (Mirzoyan et al., 2017) and, in México, a significant percentage of water resources used for aquaculture also originates from aquifers (CONAGUA, 2016). The development of this type of water implies a pumping cost (which may represent the biggest portion of energy consumption in water resources management; Fonseca et al., 2013), and could lead to aquifers overexploitation. Therefore, the use of this source for aquaculture systems, as well as surface water, must be considered in the decision-making process for water resources allocation between human consumption and food production.

Competition for water resources between aquaculture production and other water uses, as a result of water scarcity, has led to the search for alternative sources of water supply, which would increase the sustainability of aquaculture production. In aquaculture, the physical and chemical properties of supplied water are also important, as these determine the maximum load of an aquaculture production unit (Ferreira et al., 2011).

Technologies such as recirculating aquaculture systems (RAS) in which aquatic species grow under controlled environmental conditions (Zhang et al., 2018) have been designed to reduce total water volume requirements during productive cycles (Colson et al., 2015). For instance, reduction in water dependence reaches 93% with RAS in comparison with traditional flow-through farms (Martins et al., 2010).

Furthermore, RAS may reduce a set of local impacts usually associated with flow-through production systems (Dekamin et al., 2015). According to Jegatheesan et al. (2007), the aquaculture industry requires economically viable treatment systems for the reuse of wastewaters, and RASs only require a new water input of around 10% (3 m^3/

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Nomenclature

AT	Aquaculture tank
COD	Chemical oxygen demand
D	Diameter
Def	Water supply deficit
D_i	Daily demand
DO	Dissolved oxygen
H_b	Height of biofilter
IBI	Index of biotic integrity
K	Fulton’s body condition factor
L	Length
Q_i	Flow rate
RAS	Recirculating aquaculture system
RHS	Rainwater harvesting system
S	Size of the storage tank
T	Temperature
TAN	Total ammonia nitrogen
TSS	Total suspended solids
TT	Treatment train
VTR	Volumetric TAN conversion rate
W	Weight
Y_j	Efficiency of supply for size tank j

kg) per kg of fish produced per year compared to conventional flow-through systems (Bregnballe, 2015). New water inputs may even be reduced to 1% ($0.3\,m^3$/day) per kg of fish produced per year in super-intensive systems. Accordingly, RAS has emerged as a solution, limited so far to industrial production scales, for reducing volumes of residues and for improving water quality in fish production ponds (Martins et al., 2010; Ngoc et al., 2016). The implementation of these systems at a global level has been questioned because 70% of aquaculture production originates from small-scale farms (Subasinghe, 2017).

One technique that has been scarcely explored or documented for supplying new water to RAS systems and to meet its requirements during new production cycles are the rainwater harvesting systems (RHS). However, intrinsic spatial and temporal variability in rainfall is important to consider and is the main factor that alters the volumetric and qualitative modeling of rainwater supply to RAS. Previously, Tollner et al. (2004) performed hydrological balances to evaluate the use of surface water storage sources in aquaculture systems. With respect to water quality, Mohanty (2004) confirmed the viability of using rainwater from storage tanks for aquaculture. In his work, it is worth highlighting that only dissolved oxygen and total suspended solids exceeded optimal concentration ranges.

Designing, implementing and evaluating an aquaculture system implies several subjects, outstanding those involved with the water quality and quantity, fish growth performance and water savings. Abundance of studies on wastewater treatment assessment for RAS operating with specific aquatic species can be found in literature (Mota et al., 2014, 2017; Hambly et al., 2015; Li et al., 2015; Rurangwa and Verdegem, 2015; Rojas-Tirado et al., 2017; Palm et al., 2018; Strauch et al., 2018, and more). Some others tend to either enhance unit processes in wastewater treatment of RAS (Van Rijn, 2013; Lepine et al., 2015), or implement new technologies such as biodegradation of off-flavor compounds (Azaria and Van Rijn, 2018), synthetic fiber for adhesion of nitrifying bacteria (Owatari et al., 2018) and acoustic acceleration transmitters for monitoring swimming activity (Kolarevic et al., 2016).

There are also studies where water quality in RAS is related to the production yield, specifically, the fish growth performance and survival (Ingram et al., 2002; Mohanty, 2004; Ntengwe and Edema, 2008; Ben-Asher and Lahav, 2016; Venkatachalam et al., 2018; Zhang et al., 2018). Nevertheless, these studies do not regard the quantitative efficiency of water use. In this context, Wilfart et al. (2013) have set up a holistic assessment of RAS sustainability based on a Life Cycle Assessment and emergy (spelled with “m”) accounting approaches where the amount of used groundwater is considered as a non-renewable resource. On the other hand, Mirzoyan et al. (2017) have reported the efficiency of water use in a RAS where the groundwater exploitation depicts a water management challenge.

Mainly focusing on avoiding the use of either surface water or groundwater, the objectives of the present work were: a) to propose a method for dimensioning a RAS which is both filled in first place and afterwards complemented with water from a rainwater harvesting systems (RHS) and b) to evaluate the efficiency of the system based on the supply of rainwater from the RHS, the quality of water in the RAS, and performance of the development of aquatic organisms. A pilot production unit for rainbow trout (*Oncorhynchus mykiss*) was also tested with the objective of improving the capture and elimination of sediments in the aquaculture tank and implementing a treatment train to reduce space requirements. The selection of rainbow trout is supported by their need for very high-quality water for survival and optimal development. Therefore, working under these conditions, the evaluated RAS will operate efficiently on less rigorous standards with respect to required influent water volumes and quality parameters for other aquatic species.

2. Materials and methods

The pilot production unit proposed in this work has three main components (Fig. 1): an aquaculture tank (AT), an RHS, and a treatment train (TT). The quantitative and qualitative interaction of flow rates Q_{1-5} with these components can be used to estimate the efficiency of supply, water quality, and production of the system as a whole.

The efficiency of supply was estimated based on the proportion of water demand satisfied by the RHS. The efficiency of quality was validated by taking into account the minimum requirements specified during the characterization of Q_1. The efficiency of production was represented by a) increase in biomass, b) relationship between average length (L) and weight (W) of trout in the AT, c) rate of mortality, and d) Fulton’s body condition factor K (Froese, 2006).

Based on the type and number of fishes to be cultivated, the first stage (Fig. 21) in designing a closed aquaculture system is estimating the volume of the AT, the flow rate (Q_1), and the water quality required for adequate fish growth. For rainbow trout (*Oncorhynchus mykiss*), the number of organisms per cubic meter can be estimated as a function of the growth phase and fish weight (Table 1) according to the recommendations of Woynarovich et al. (2011). Rainbow trout species

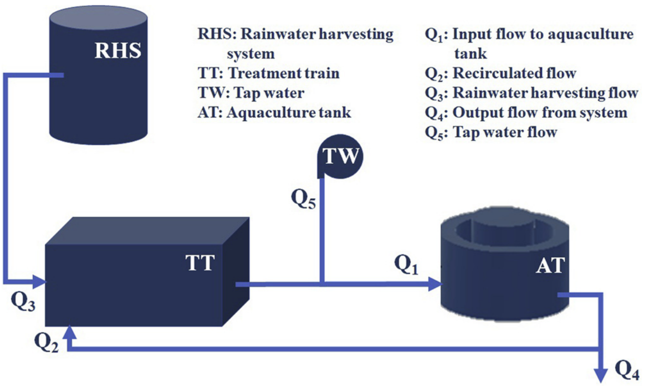

Fig. 1. Conceptual model of a closed aquaculture system design and assessment.

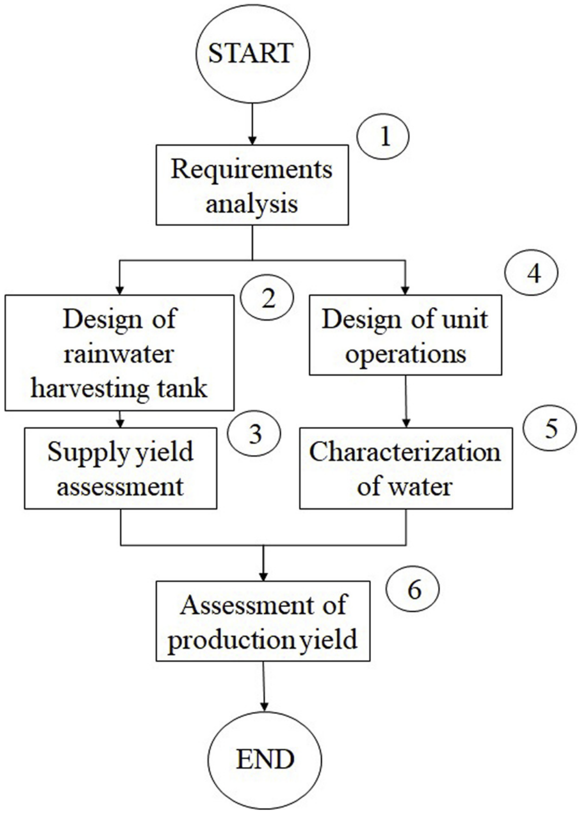

Fig. 2. Flow chart of design and assessment of a closed aquaculture system based on rainwater harvesting.

Table 1
Production of rainbow trout in lined and concrete tanks (Woynarovich et al., 2011).

	Table fish			
	250 g/fish		500 g/fish	
	From	To	From	To
Quantity of fish (fish/m^3)	60	100	30	50

was selected due to its high-required water quality for healthy development. The research strategy consisted of finding solutions for one of the most demanding species (rainbow trout) in terms of water quality, guaranteeing somehow the possible rearing of other less demanding species. For instance, tilapia is more tolerant than most species to different environmental parameters like salinity, low dissolved oxygen, high TAN concentrations (Lim and Webster, 2006).

Also, rainbow trout has been considered as an intolerant species and cataloged as metric 5 in the index of biotic integrity (IBI; Grabarkiewics and Davis, 2008) this means that the rainbow trout is very sensitive to various environmental changes. Other species like the Channel Catfish is capable of maintaining populations in turbid streams, it scores as a tolerant and great river species (metric 6 of the IBI: species tolerant to changes in habitat and water quality).

Required water flow to the AT apparently adheres to a second-order mathematical model as a function of fish length and weight. For market size fish (Fig. 3), the maximum required flow rate is reached for fish with a length of 20 cm; under the present scheme, this value was used for designing the tank.

With respect to quality, among the main parameters observed in previous studies (Ingram et al., 2002; Ntengwe and Edema, 2008; Bregnballe, 2015) which should be monitored, are total ammonia nitrogen TAN, dissolved oxygen DO, pH, alkalinity, and temperature T (Table 2). Timmons et al. (2010) additionally recommend a rate of water exchange near 1.5 of the total volume per hour.

A circular AT (Fig. 4) with a central settler tank that receives peripheral influent is proposed. The peripheral influent creates a vortex flow toward the settler to support fish health (Timmons et al., 2010). Effluent extraction is based on the principle of hydro cyclones for solids to be captured and separated by means of continuous separation and minimum required area (Mailapalli et al., 2007; García-Pulido et al., 2011). Although some tanks present diameter/depth ratios up to 5 for volumes greater than 300 m^3 (Gorle et al., 2018), some diameters of tanks smaller than 6 m^3 (Espmark et al., 2017; Lee et al., 2013) range between once and twice the depth. Furthermore, Espmark et al. (2017) found that growth performance in 3 m^3 tanks was comparable to the reference sea cages. Blanco (1995) suggests that the water depth can reach up to 1 m in recirculation tanks for market size fish.

Water supply to the AT should mainly be satisfied by return flow from the wastewater treatment train. However, the first fill and complimentary water demands are proposed to be satisfied by an RHS (Stage 2 of Fig. 2). In this case, a storage tank is required to regulate the non-uniform spatial and temporal distribution of rainfall (Su et al., 2009). Following the methodology of Fonseca et al. (2017), the size of the storage tank S (m^3) was selected using an iterative process, evaluating the efficiency of supply Yj for size j of tank S (Stage 3 of Fig. 2)

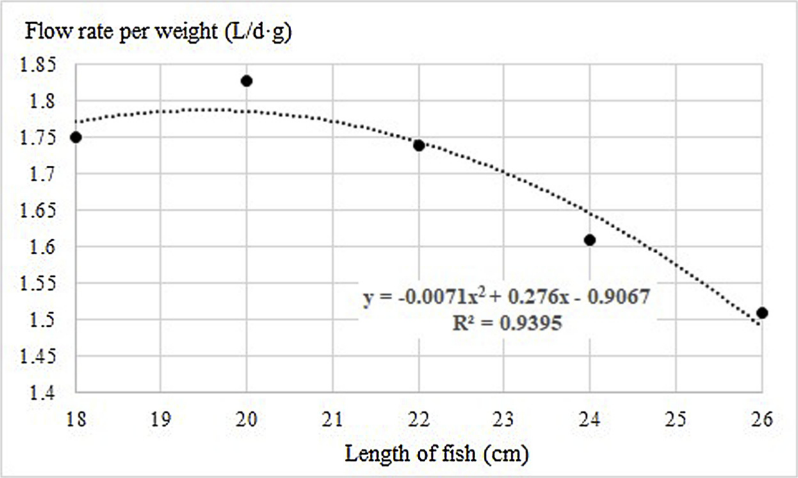

Fig. 3. Water flow rate required for trout farming (Table fish). Elaborated with data from Blanco (1995).

Table 2
Water quality thresholds for trout farming.

Parameter	Units	Rainwater Mean value	Optimum range for trout production	Reference
Dissolved oxygen	(mg/L)	6.6	> 5.0	Blanco (1995)
			7.8	Timmons et al. (2010)
COD_T	(mg/L)	4.9	< 150	García-Pulido et al. (2011)
TAN	(mg/L)	0.92	< 1.0	Timmons et al. (2010)
$N\text{-}NO_2^-$	(mg/L)	0.021	< 0.5	Timmons et al. (2010)
			< 0.39	Russo and Thurston (1991)
$N\text{-}NO_3^-$	(mg/L)	1.7	< 1 360	Russo and Thurston (1991)
TSS	(mg/L)	14		Blanco (1995)
			< 80	Timmons et al. (2010)
Ca	(mg/L)	1.41	> 50	Klontz (1991)
			4–160	Timmons et al. (2010)
K	(mg/L)	0.18	< 5	Timmons et al. (2010)
Mn	(mg/L)	0.25	< 0.01	Timmons et al. (2010)
Na	(mg/L)	0.22	< 75	Timmons et al. (2010)
Cl^-	(mg/L)	2.30	< 250	DOF (1989)
SO_4^{-2}	(mg/L)	< 5.0	< 50	Timmons et al. (2010)
Fe	(mg/L)	0.14	< 1.0	Klontz (1991)
			< 0.15	Timmons et al. (2010)
Mg	(mg/L)	0.19	< 15	Timmons et al. (2010)
pH		5.5	6.7–8.5	
			6.5–8.5	Klontz (1991)
			6.5–8.0	Timmons et al. (2010)
Alkalinity	(mg/L Ca CO_3)	3.21	50–300	Timmons et al. (2010)
Acidity	(mg/L $CaCO_3$)	5.16		
Temperature	(°C)	17	14–16	Timmons et al. (2010)
			10–15	DOF (1989)

TAN: Total Ammonia Nitrogen.

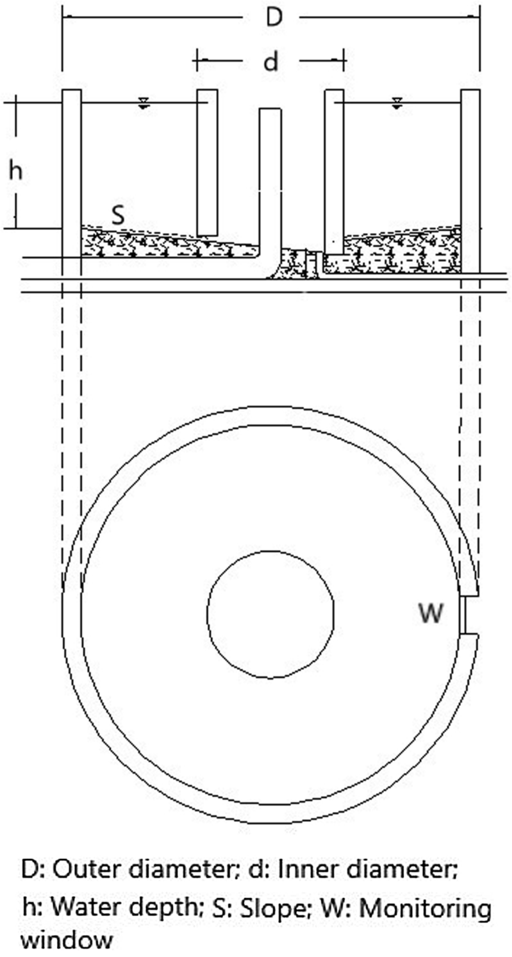

Fig. 4. Cylindrical aquaculture tank for a recirculating system.

based on the probability of non-exceedance according to a Beta probability distribution function (Donini et al., 2015).

The efficiency of supply Yj (Eq. (1)) is a function of daily deficit Def_i (m^3/day) and daily demand D_i (m^3/day). Def_i (Eq. (2)) is positive when D_i is greater than the sum of water available from rainfall q_{ei} (m^3/day) and previously-stored water s_i (m^3/day). Available water is the product of the catchment area and accumulated rainfall. The time scale for evaluating supply efficiency can be annual or equivalent to the production cycle of a particular aquatic organism.

$$Y_j = 1 - \frac{\sum Def_i}{\sum D_i} \tag{1}$$

$$Def_i = \begin{cases} 0\, if\ q_{ei} + s_i \geq D_i \\ D_i - q_{ei} + s_i\ otherwise \end{cases} \tag{2}$$

To achieve water recirculation, the proposed treatment train (TT) begins with a treatment tower containing three units (Stage 4 of Fig. 2): a) biofilter (trickling filter), b) sand column, and c) settler (located in the center of the AT). The treatment tower approach presents some advantages like dissolved Oxygen saturation in water and exiting the biofilter without electric energy requirements. Processes of nitrification and removal of solids occur in the sand column. Solids suspended in the AT are removed by the settler tank. The configuration of the unit processes of the TT is supported by previous studies (Díaz-Delgado et al., 2000; García-Pulido et al., 2011; Gallego-Alarcón and García-Pulido, 2017), and the tower configuration economizes space and construction materials (Badiola et al., 2018).

Biofilter efficiency is usually measured by the volumetric TAN conversion rate (VTR) as a function of the supplied feed (Malone and De Los Reyes, 1997; Colt et al., 2006; Drennan et al., 2006; Malone and Pfeiffer, 2006). In addition, the relationship of VTR with biomass can be used to dimension the biofilter (Badiola et al., 2018).

The diameter (D_b) of the biofilter and height (H_b) of the media column were estimated based on oxygen requirements, ammoniacal nitrogen production, and hydraulic head, among other variables (Table 3). According to Wheaton et al. (2000), oxygen demand for trout is 0.25 kg O_2/kg of feed at a feed rate of 2%, and the production of

Table 3
Sizing requirements for trickling filter. Based on Timmons et al. (2010).

Variable	Expression	Inputs
Required Dissolved Oxygen	$R_{OD} = a_{OD} \bullet r_{ali} \bullet \rho \bullet V_E$	a_{DO}: Oxygen Demand r_{ali}: Feed ratio ρ: Sow density V_E: Aquaculture tank volume
Required surface area	$A_{Am} = \frac{P_{AM}}{TAA}$	P_{Am}: Daily ammonia Nitrogen production TAA: Aerial ammonia nitrogen remotion rate
Bed media volumen	$V_{Am} = \frac{A_{AM}}{ASE}$	ASE: Specific Surface
Cross section and filter diameter	$A_t = \frac{Q_D}{CH}$; $D = \sqrt{\frac{4A_t}{\pi}}$	Q_D: Design Flow rate CH: Hydraulic head
Bed media height	$H_B = \frac{V_{Am}}{A}$	

ammoniacal nitrogen is 0.03 kg/kg of feed considering an aerial respiration rate of 0.25 kg/m^2 day.

With respect to the sand filter, the dimensioning recommended by Metcalf and Eddy (2014) is 230 m^3/m^2 day. Besides some filtration systems count with a gravel media of 0.50–0.90 m (median particle size of 10.5 mm) above the sand layer due to that pollutant removal performance is not influenced by either the hydraulic head or clogging (Hatt et al., 2007). However, to decrease its height it is proposed, supported by local previous studies (García-Pulido, 1999; Fall, 1999; García-Pulido et al., 2011), including a column with five 0.05 m layers containing graded gravel of 2.57, 3.18, 6.35, 12.7 and 19.05 mm. The conventional height for a sand filter is 0.45 m, with an effective diameter (D_{10}) of 0.36 mm and a uniformity coefficient (D_{60}/D_{10}) of 1.47 (Metcalf and Eddy, 2014). In the present study, an additional 0.45 m of height is proposed to avoid the fluidization of sand and to create a freeboard of 0.10 m.

Stage 5 was the characterization of water quality. The parameters of TAN, nitrite, nitrate, chemical oxygen demand (COD), alkalinity, and total suspended solids (TSS) were measured two times per week using a random stratified sampling strategy as a function of biomass to better estimate the variance (Lohr, 2000). Because of the low expected concentrations of TAN and NO_2-N, the VTR (Eq. (3)) was represented by a simple linear regression model (Drennan et al., 2006; Malone and Pfeiffer, 2006; Guerdat et al., 2010), as Eq. (3).

$$VTR = Q_r(TAN_I - TAN_E)\Big/V_b \tag{3}$$

where VTR is the volumetric TAN conversion rate (g-TAN/m^3 d); TAN_I and TAN_E are the concentrations of total ammonia nitrogen (g-TAN/m^3) in influents and effluents, respectively; Qr is the rate of flow through the filter (m^3/day); and V_b is the total volume of the biofilter medium (m^3).

The final stage involved evaluating the pilot unit of the aquaculture system. Biomass and the length-weight relationship of trout were used as indicators of the physical condition of trout, although variation in temperature, DO, and biomass density, among other variables, also affected the physical condition (Klontz, 1991). As an exploratory analysis or as a rough assessment, conventionally, higher values of this relationship depict an accepted fish development in a tank.

In relation with mortality ratios, values from 29 to 40% can be seen normally in open and mangrove-aquaculture systems (Venkatachalam et al., 2018), values from less than 5% to 46% in closed systems depending on tank size (Espmark et al., 2017) and in contrast, values of survival higher than 90% are observed in RAS (Zhang et al., 2018). For this work, an acceptable mortality rate was set at 15%, as established by Blanco (1995). Also, higher values of Fulton's body condition factor K (Ricker, 1975; Nash et al., 2006) were assumed in the present study to be indicators of better fish development for fish of the same length. This growth factors worked indirectly as indicators of good water quality for the survival of the fish.

2.1. Study area

The design and evaluation of the proposed recirculation aquaculture system were carried out in the facilities of the Inter-American Institute

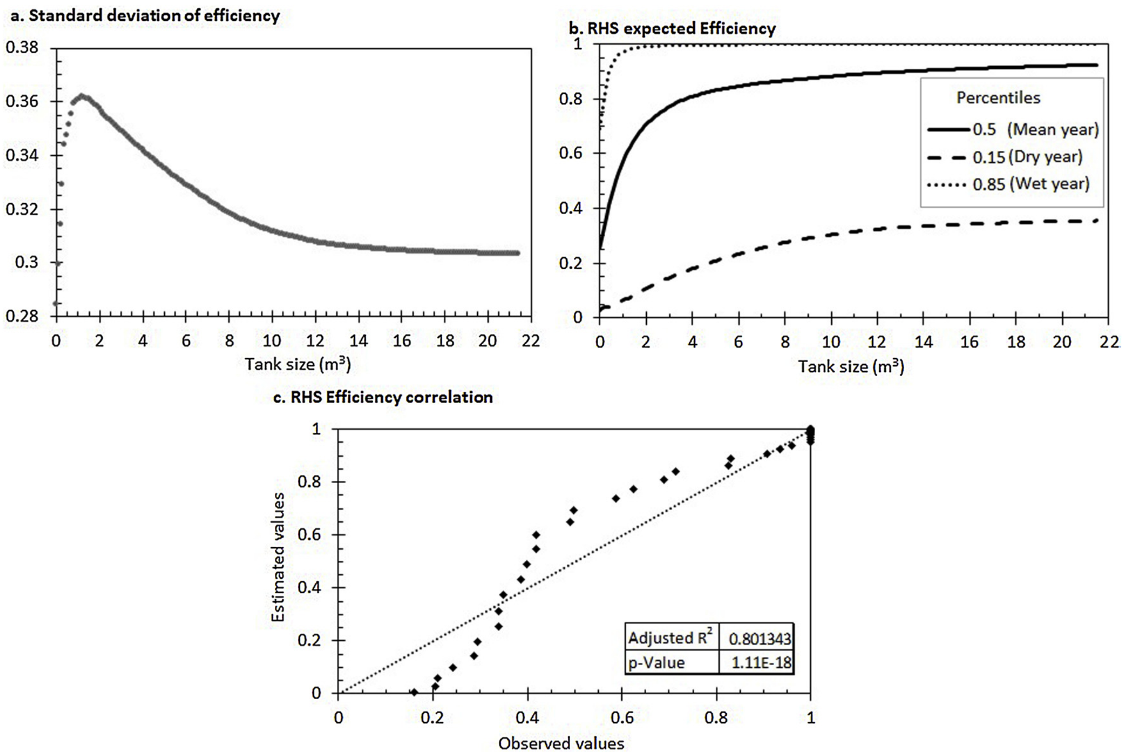

Fig. 5. Efficiency of the rainwater harvesting system.

of Water Science and Technology (IITCA-UAEMex) located in the highlands of central Mexico (99°43′W, 19°24′N). The system was projected to house 418 rainbow trout (*Oncorhynchus mykiss*) from a local farm, Llano del Rayo, in Temoaya, State of México (99°32′W, 19°33′N, 2600 m.a.s.l.). The trout had an average length and weight of 19 cm and 287 g, respectively.

It is worth mentioning that in central Mexico, trout production in 2013 reached 3700 tons, which was generated from 489 production farms (García-Mondragón et al., 2013), in 2017 was 6471 tons of 14,197 tons of the trout country production (CONAPESCA, 2017). Therefore, this region is one of the greatest national producers of trout in the inner country. Furthermore, trout production (ton) has increased by 9.16% annually over the last 14 years. Most production units are small-scale farms (< 5 ton/unit year) and consume more than 329 hm^3/year of fresh water (5% is provided with groundwater; OCLSP, 2017).

Finally, the study area has a temperate sub-humid climate and an average annual accumulated rainfall of 900 mm in the Valley of Mexico (Díaz-Delgado et al., 2014). Rainfall data were provided by the Development Management System (SiGeDes; Hidalgo et al., 2016), and daily accumulated rainfall values were calculated based on the method outlined by Vilchis-Frances et al. (2015). Average daily rainfall was 2.36 mm, with a standard deviation of 4.49 mm; the water catchment area regarded for this experimental farm was 100 m^2.

3. Results

Given the size of the fish introduced to the aquaculture system, the required volume of the cylindrical AT was between 4.3 and 7.0 m^3 (Table 1). The required water flow was about 181,130 L/d (Fig. 3), assuming fish grow up to 26 cm. The AT was thus constructed to have a diameter (D) of 3 m, a settler tank with 1 m of diameter, and a projected water depth of 1 m. The AT net water volume was 6.3 m^3, and the water exchange rate was 1.2 times per hour.

3.1. The efficiency of the rainwater harvesting system

Besides a first filling of the AT, new water demand of 400 L/day was considered upon designing the RHS based on a previous study (García-Pulido et al., 2011). New water is required because of evaporation, sediment drainage, sampling, potential leaks, filter backwash, and wastewater treatment.

The daily mass balance of water was calculated based on 50 years of rainfall records (from 1960 to 2009). A large dispersion in the annual efficiency of the RHS was found for tank sizes up to 1.2 m^3 (Fig. 5a). With increasing tank sizes, the variation in annual efficiency decreases until reaching an approximate standard deviation of 30%. The expected efficiency of the RHS was found to have a non-significant variation for a tank size of at least 21.5 m^3.

A Beta probability distribution function was adjusted to rainfall records. Dry, average, and wet years were associated with the 15th, 50th, and 80th percentiles, respectively. The annual efficiency of the RHS (η_s) as a function of tank size (Fig. 5b) tends toward 100% for a wet year and 92% for an average year. In the worst scenario, an efficiency of 36% is expected. Given standard commercial tank sizes, a storage capacity of 22 m^3, corresponding with three tanks of an approximate capacity of 7.3 m^3, was selected. These dimensions had acceptable values for the coefficient of determination (Fig. 5c) at a high level of significance ($p\text{-value} < 0.05$).

3.2. The efficiency of the water treatment

With respect to the dimensions of the water treatmen train (Fig. 6), the diameter of the tower was 1.36 m. The height of the biofilter packing was 0.80 m (specific contact area of 414 m^2/m^3), and the height of the sand filter was 1.5 m. A submersible pump was installed (Little Giant 5-MSP) with 1/6 HP and a Venturi system at the outflow to maintain the DO concentration within an optimal interval. The effluent flow to the pump was equilibrated to the influent flow to the AT to achieve a homogenous mixture of DO. Therefore, water supplied to the AT (Table 4) maintained acceptable levels of TAN and pH at the entrance and exit. The temperature was 4.8% higher than the established range in Table 2. Before starting the RAS operation, the rainwater characterization was carried out once for a mixture sample after the tank of the RHS reached its capacity (Table 2). Later, characterization of the input water to the AT covers quality variations among the remaining water in the tank, new rainwater entering to the RHS and the recirculated wastewater.

On the other hand, the alkalinity of the inflow was 6.6–8.9% below the required values reported by Timmons et al. (2010), but respecting the minimum value given by Biesterfeld et al. (2003) (Table 2). In this context, water from the RHS required conditioning to increase the pH and alkalinity. Forty, 25 and 40 g of sodium bicarbonate, lime, and sea salt were dissolved in the RHS tank on a daily basis.

The alkalinity of the outflow increased by 18%. Considering that the consumption of a balanced feed (containing 45% protein and 16% fat) was 157 kg, corresponding with a daily ration of 1.13% ± 0.23% of trout weight (feed conversion rate equal to 1.37), the consumption of $NaHCO_3$ was 0.08 Kg/Kg of feed. This allowed the system to remain the conversion from TAN to NO3-N, in spite of the nitrifying bacteria consumed less than the half of sodium bicarbonate reported in the literature (0.15–0.19 Kg; Davidson et al., 2011; Summerfelt et al., 2015).

With respect to other water quality parameters, the biofilter resulted

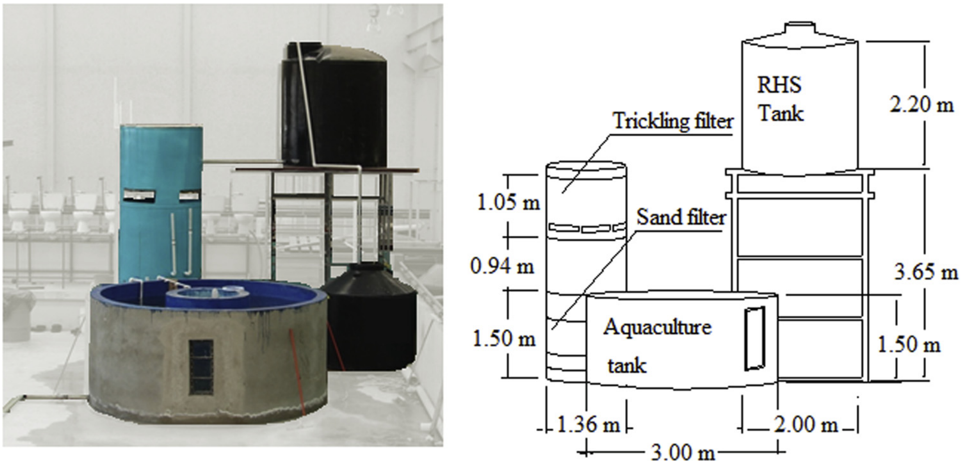

Fig. 6. Sizing of aquaculture system for the study case.

Table 4
Observed concentrations of quality water parameters.

	COD (mg/L)		TAN (mg/L)		NO_2 (mg/L)		NO_3 (mg/L)		TSS (mg/L)	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Rainwater	4.9		0.92		0.021		1.7		–	
AT	43.81 ± 0.37	51.58 ± 041	0.27 ± 0.0123	0.80 ± 0.0125	0.201 ± 0.006	0.250 ± 0.006	59.14 ± 0.21	58.77 ± 0.18	2.06 ± 0.033	3.64 ± 0.03
Trickling filter	49.27 ± 0.33	46.60 ± 0.44	0.80 ± 0.012	0.66 ± 0.012	0.264 ± 0.005	0.312 ± 0.006	59.13 ± 0.17	58.13 ± 0.19	3.62 ± 0.04	3.73 ± 0.04
Sand filter	46.60 ± 0.44	43.81 ± 0.37	0.66 ± 0.012	0.27 ± 0.0123	0.312 ± 0.006	0.201 ± 0006	58.13 ± 0.19	59.14 ± 0.21	3.73 ± 0.04	2.06 ± 0.033

	DO (mg/L)		Temperature (°C)		pH		Alkalinity (mg/L $CaCO_3$)	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Rainwater	6.6		17		5.5		3.21	
AT	5.35 ± 0.08	4.86 ± 0.07	16.77 ± 0.12	16.76 ± 0.13	6.99 ± 0.07	6.95 ± 0.07	46.11 ± 0.56	54.46 ± 0.57
Trickling filter	6.54 ± 0.04	6.80 ± 0.03	16.91 ± 0.12	16.82 ± 0.12	6.98 ± 0.08	7.13 ± 0.07	65.14 ± 0.69	51.42 ± 0.56
Sand filter	6.80 ± 0.03	5.35 ± 0.08	16.82 ± 0.12	16.77 ± 0.12	7.13 ± 0.07	6.99 ± 0.07	51.42 ± 0.56	46.11 ± 0.56

COD: Chemical Oxygen Demand; TAN: Total Ammonia Nitrogen; NO2: Nitrite; NO3: Nitrate; TSS: Total Suspended Solids; DO: Dissolved Oxygen; AT: Aquaculture tank.

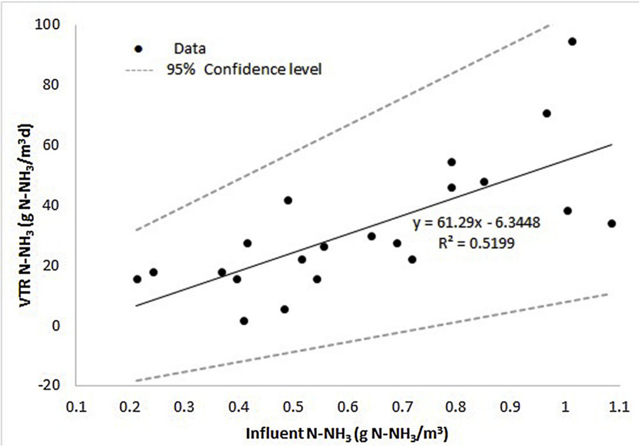

Fig. 7. VTR tend in trickling filter.

in a slight increase in NO_2, TSS, and DO, but the process of sand filtering achieved a reduction in these parameters of 36%, 43%, and 21%, respectively, with respect to the inflow. Also, the COD decreased by 21%, whereas NO_3 showed the least variation (1.6%).

According to several studies (Ntengwe and Edema, 2008; Venkatachalam et al., 2018), an inverse relation was observed between water temperature and DO. It is assumed that the range of observed temperatures and the additional water volume inputted from the RHS enabled the DO levels in the AT to be equilibrated.

With respect to the VTR, the biofilter, as well as the sand filter showed a strong correlation ($R^2 = 0.72$ and $R^2 = 0.91$, respectively) with TAN content (Figs. 7 and 8). Unexpectedly, the greatest nitrification occurred in the sand filter. The linear dependence between low concentrations of TAN and VTR agrees with previous evaluations of biofilters (Zhu and Chen, 1999; Guerdat et al., 2010; García-Pulido et al., 2011).

Although VTR values may reach 267–374 g-TAN/m^3 d in fluidized bed reactors (Zhu and Chen, 1999, 2001; Guerdat et al., 2010) and 704–4917 g-TAN/m^3 d in fluidized sand filters (Ling and Chen, 2005; Guerdat et al., 2010), the average VTR in the present configuration (35 ± 41 and 120 ± 43 g-TAN/m^3 d in bio filtered and sand filtered water, respectively) is similar to that reported by Malone and Pfeiffer (2006), corresponding with a removal rate of 73.53%.

3.3. The efficiency of production

The required sample size for determining the production efficiency at a precision of 12.5% and confidence level (1-α) of 95% was 67

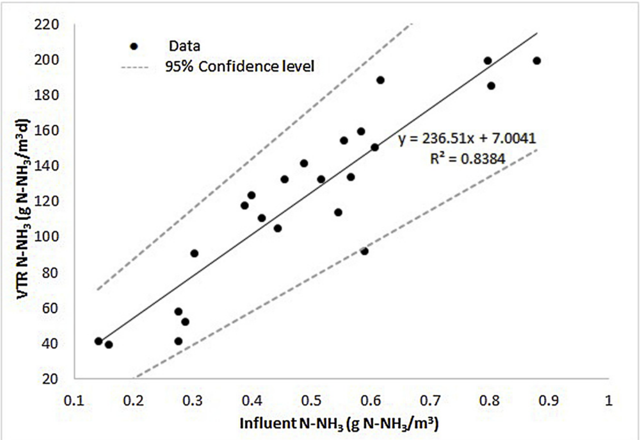

Fig. 8. VTR tend in sand filter.

organisms. After 121 days of growth, the total increase in biomass was 60.54 kg (a 50% increase with respect to initial weight). Trout had an average length of 34 cm and an average weight of 644 g. The weight increase (0.5 g/day) is within the interval growth described in the literature: 0.3 g/day in Klontz (1991), 0.8 g/day in Ingram et al. (2002), and 0.95 g/day in Blanco (1995). In terms of biomass, the designed tank size would allow a larger number of organisms in previous growth stages, e.g. fingerlings. In the present study case, the biomass reached would allow a set of 900 fingerlings up to 20 g/organism. In terms of collected sediments, small fish converts fish feed at a better rate than large fish (Bregnballe, 2015), thus the table fish size depicts the critical conditions in the operation of filters. Therefore, it is suggested a conventional operation of filters. That means, for example, a backwash frequency of the filter of four to eight times per month (Metcalf and Eddy, 2014) depending on the clogging effect on the trickling and sand filter.

The mortality rate was 2% considering a density of 29.1 kg/m^3 (66 organisms/m^3). Traditional farms using open systems require around 210,000 L of water to produce one kg of fish (Timmons et al., 2010). However, in the present system, only 178.3 L/kg of trout was required and entirely supplied by the RHS.

The configuration of the recirculation system in the present work led to better fish development (Fig. 9) compared to systems with similar conditions (García-Pulido et al., 2011) and even compared to systems with controlled temperatures conditions (between 13 and 15 °C; Klontz, 1991). A proportional increase in weight relative to length was observed, ranging from 31% (for fish 22 cm in length) to 51% (for fish 38 cm in length), in relation to the development reported by Klontz (1991).

Trout development was also evaluated according to Fulton's body condition factor K (Fig. 10). Considering average trout length, the K factor calculated in the present work was 20% higher in comparison to the studies of García-Pulido et al. (2011) and Klontz (1991).

Additionally, lower production of TAN relative to biomass was found compared to García-Pulido et al. (2011) (Fig. 11). Overall, TAN production showed a slightly linear tendency as a function of biomass. Although production was lower than in García-Pulido et al. (2011), a similar gradient (0.0063 and 0.008 mg TAN/L kg, respectively) was observed. These marginal values can be used for future biofilter designs (applicable for densities between 16 and 29 kg/m^3).

Regarding the cycle of the fish growth (121 days), the water efficiency of the current RAS (0.18 m^3/Kg) shows a non-exceedance probability about 2% compared with those rainbow trout farms reported by Mirzoyan et al. (2017) that operate with groundwater (Fig. 12). This applies the same way in the worse scenario (dry year) where the system would require 0.07 m^3/kg of fish from an alternative source like groundwater from deep wells in the study zone.

It is important to highlight that solely harvested rainwater was used for the first year to fulfill the AT requirement and the exchange water demand. Therefore, the RHS could depict a safety source in case the recirculated water would not be available for any reason. In relation to the implementation of the type of aquaculture production system outlined in the present study within the study area, at least two operating units would be required to achieve the typical production volume of a small-scale farm (1 ton/year). However, the implementation of this system in local farms is subject to a complex array of factors that remain outside the reach of the present study. For example, Badiola et al. (2017) claim that energy should be one of the main aspects understudy for the assessment of RAS.

The need for more complex oxygenation mechanisms might imply an increase in energy consumption of 7.69–65.5 kW h/kg of trout (Badiola et al., 2018; Rosati et al., 1994). Even so, any increase in energy consumption may be partially compensated by energy savings generated by the RHS, which prevents the need to extract groundwater, especially considering that 77,000 kW h is consumed annually to extract water from deep wells in the study region (Fonseca et al., 2013).

4. Conclusions

In this work, a pilot aquaculture farm for trout production was designed and dimensioned to minimize and substitute water flow from first-order sources (usually springs or extracted groundwater) with the recirculation of treated water and the use of harvested rainwater. Unlike previous studies, it was proposed an integrated assessment of the design efficiency from three perspectives: the supply of rainwater, the quality of treated water, and the production yield.

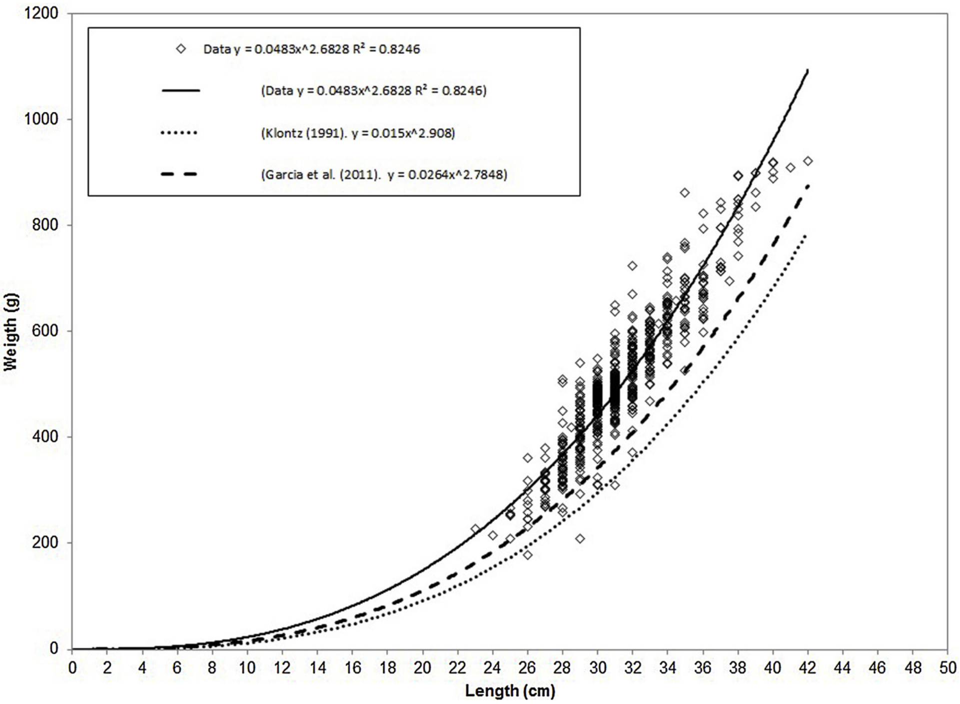

Fig. 9. Trout development comparison among different studies.

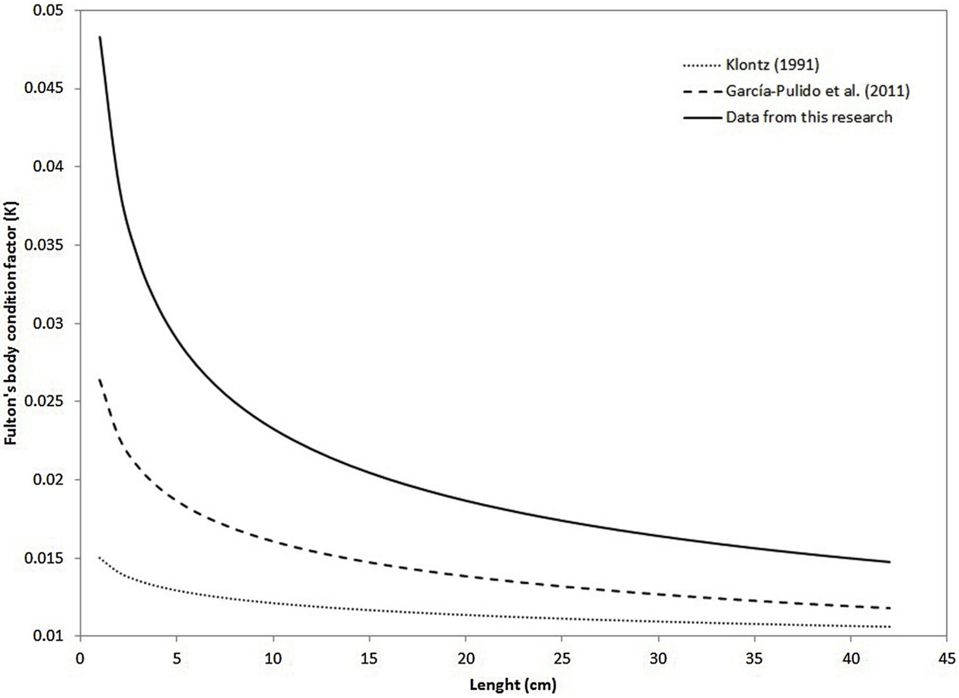

Fig. 10. Fulton's body condition factor K comparison among different studies.

The efficiency of water supplied by the RHS was evaluated based on a daily mass balance of water. This allowed estimating the required water storage capacity at which variation in supply would not be significant. This tank size was not just the minimum value to guarantee at least 92% of the demanded water in average hydrological conditions but demonstrated to be able to fill the tank for the first time.

To achieve water recirculation, a configuration based on a treatment tower and a circular AT with a settler tank was proposed. The treatment tower contained a biofilter and a sand filter. Outflow water had acceptable values of pH, TAN, and alkalinity. The temperature was slightly above (4.8%) the suggested range but did not negatively impact trout development. Overall, TAN content in outflow water showed a linear dependence on the VTR in the biofilter ($R^2 = 0.72$) as well as in the sand filter ($R^2 = 0.91$). On the other hand, the settler tank located inside the AT operated according to the principle of hydro cyclones to separate and capture sediments during the operation of the system.

Trout showed better development in terms of length and weight compared to similar previous studies. Also, in contrast to other studies in the literature, the mathematical models for dimensioning the system were calculated as a function of biomass in the tank instead of the

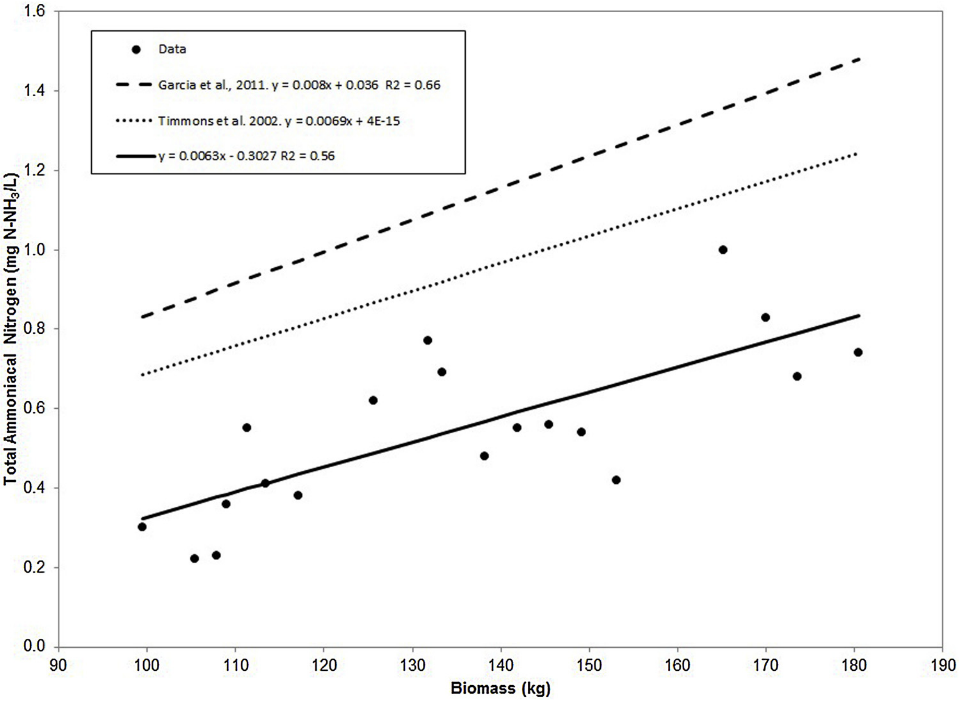

Fig. 11. Ammonia nitrogen production by biomass of fish.

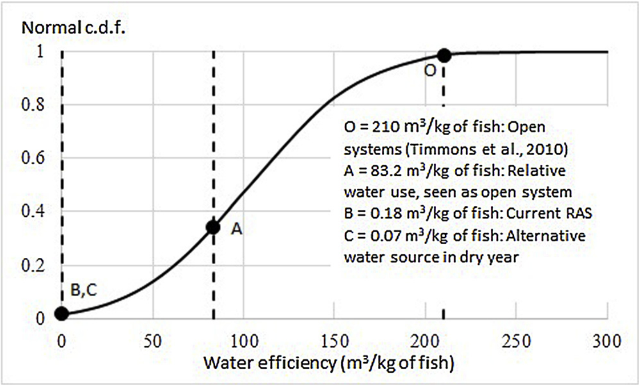

Fig. 12. Water efficiency relative to biomass.

quantity of supplied feed. Therefore, this method confirmed the applicability of this alternative criterion for designing biofilters and aquaculture systems (applicable for a biomass density of 16–29 kg/m^3).

The high yield (178 L/Kg of fish) of the present aquaculture system, compared with open systems (210,000 L/Kg of fish), also supports its applicability for increasing production efficiency using highly nutritive feed under conditions of limited access to open flow water sources.

Finally, despite evaluating the efficiency of the production system from three perspectives (supply, quality, and production), a more holistic analysis of the energy consumption of the entire process, the consumption of renewable and non-renewable resources, and the relationship between socioeconomic impacts and benefits is required.

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