Effects of four medicinal plants on the bioeconomic analysis and water-use efficiency of Nile tilapia, *Oreochromis niloticus* fry nursed under a small-scale aquaponics system

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Abstract. This study aims to assess the efficiency of four medicinal plant species in purifying water discharged from fish tanks. Five treatments in three replicates were performed. Four aquaponics treatments were compared to a traditional fish nursery system (control) using 20% daily water exchange rate, compared with 0.5% in aquaponics treatments. Twelve pilot-scale aquaponics units were designed, installed, and operated. Rosemary (*Rosmarinus officinalis* L.), mint (*Mentha spicata* L.), marjoram (*Origanum majorana* L.), and thyme (*Thymus vulgaris* L.) plants were cultivated at 25 plants/hydroponics unit, with fish:plant ratio of 88:1. Tilapia (*Oreochromis niloticus*) fry (0.134 g fish^{-1}) was stocked at 2200 fry m^{-3} and fed with fine powdered diet containing 30% protein at 8-10% of body weights daily, through four meals, for 30 days. Growth parameters of both fish and plants, water quality indices, economic evaluation, and water-use efficiency were evaluated. Thyme plant improved significantly ($p \leq 0.05$) the growth of tilapia fry by 1.6-times compared to the other plants. Rosemary exhibited the best values of survival and feed conversion ratio (FCR). The fresh and dry shoot biomass of rosemary (g/plant) and Log10 (shoot:root) improved by 2.3-times and 1.2-times than that of mint, respectively. The NO_3-N and NH_4-N contents in water with rosemary were 2.4-times lower than the control. However, the toxicity of NH_3-N during the last week in the aquaponics with thyme (~0.4 ppm) and marjoram (~0.2 ppm) was probably the reason for the death of both plants. For the economic evaluation, the internal rate of return (IRR) for the aquaponic system with rosemary was 2.65-times higher than the control. Technical and financial water-use efficiency of the aquaponics system were 7.1- and 16-times higher than the control respectively. It can be concluded that aquaponics is a promising system for nursing tilapia fry at high density, but further studies should be done to maintain water quality parameters within the safe levels for both fish and plant.

Key Words: aquaponics, Nile tilapia, medicinal plants, performance, economic, water-use efficiency.

Introduction. The increased human population and the lack of fresh water resources are considered to be great limitations for sustainable food production at international scale (FAO 2018). Accordingly, aquaculture intensification is crucial for food safety and security to meet the prospective increase in the world population (Tidwell 2012). However, the maintenance of desirable water quality for high growth performance of fish remains a remarkable challenge for aquaculture scientists (Rakocy et al 2006; FAO 2018). Consequently, the low quality of freshwater resources and land degradation are considered as great limitations for the extension of aquaculture. There is a necessity for developing fish production systems to meet the problems mentioned above.

In recent decades, aquaponics is a realistic option for successful operating/managing of aquaculture farms under limited water resources to maintain water quality, ensuring safe fish production and mitigating environmental pollution (Rakocy 2012). The nutrient-rich wastewater from rearing fish can be recirculated and used for growing a variety of crops while plant roots could remove the toxic components such as the excess of ammonia, nitrates and other elements (Rakocy 2012; Goddek et al 2015). Aquaponics, as sustainable and eco-friendly technology, is an integration of a recirculating aquaculture system (RAS) with crops growing hydroponically (Rakocy et al 2006; Rakocy 2012; Goddek et al 2015). This RAS is designed to allow rearing vast amounts of fish in relatively small volumes of water due to the biofiltration of wastewater by plant roots, owing to the removal of toxic compounds to fish (Rakocy et al 2006; Rakocy 2012). Many hydroponics systems have been designed for growth and health improvement of fish through the root system of vegetables, herbs and flowering crops (Rakocy 1997; Graber & Junge 2009). Plant roots combined with beneficial bacteria turnover the toxic ammonia to nitrate (a non-toxic form of N to fish) and uptake both NH_4^+ and NO_3^- from the wastewater (Rakocy 1997; Rakocy et al 2006; Graber & Junge 2009; Rakocy 2012).

Egypt occupies the 9th rank of global fish production and the 3rd in global tilapia production after China and Indonesia (FAO 2018). Furthermore, freshwater fishes contribute to more than 96.5% of Egyptian fish production (Shaalan et al 2018). In our study, a small-scale aquaponics system for tilapia hatchery with the advances of less water-consumption, maintaining/enhancing water quality, and highly intensive tilapia fingerlings production (> 2000 fish fry per one m^3 water) was implemented. The objectives of the present study are to: (1) develop an aquaponics system for nursing high-density tilapia (*Oreochromis niloticus*) fry with less water consumption; (2) compare the efficiency of different medicinal plant species in purifying water discharged from fish tanks; and (3) compare the economic evaluation and water-use efficiency of both traditional and aquaponics nursery systems. Medicinal plants belonging to the family Lamiaceae (rosemary, *Rosmarinus officinalis* L., mint, *Mentha spicata* L., marjoram, *Origanum majorana* L., and thyme, *Thymus vulgaris* L.) were selected for the evaluation because of their high price and multiple medical uses.

Material and Method

Fish and experimental site. This experiment was conducted at the Fish Farming and Technology Institute, Suez Canal University, Ismailia, Egypt, during May 2018. Nile tilapia fry purchased from a private fish hatchery in Kafr El-Sheikh Governorate, Egypt were acclimatized for one week.

Design and components of the aquaponics system. Twelve pilot-scale aquaponics units with an artificial LED lighting system were designed and installed. As shown in Figures 1 and 2, the aquaponics system consisted of the following components: (1) 12 circular fiberglass tanks (each having one m^3, 1.0 m diameter) for rearing tilapia fry, (2) 12 floating-raft hydroponics units, (3) biological filter, (4) aeration system for the fish tank and hydroponics units, (5) a submersible aquarium pump for water recirculation in the designed aquaponics system, (6) automated LED lighting system (working for 12 hours per day). To implement this module, by-product plastic containers were reused. Floating-raft hydroponics system of deep-water culture is constructed from half of the 200 L plastic drum (0.925 m length × 0.585 m diameter and 3.5 mm thickness). A half inch PVC pipe with a plastic valve was used for supplying water to the hydroponics container to control the water flow by a submersible pump in the fish tank (Figure 2).

Bio-filtration system/layer. The biofilter was established by filling a 50 mm at the bottom of the hydroponics container with a mixture of zeolite and gravels (a 1:5 ratio, v/v) to enhance the growth of nitrifying bacteria (i.e., *Nitrosomonas* and *Nitrobacter*) under plant roots. The designed biofiltration system was adopted with modifications from the described biological aerated filter in a study by Chang et al (2009). The design of the experimental unit was drawn in 3D by SketchUp Pro 2016 software.

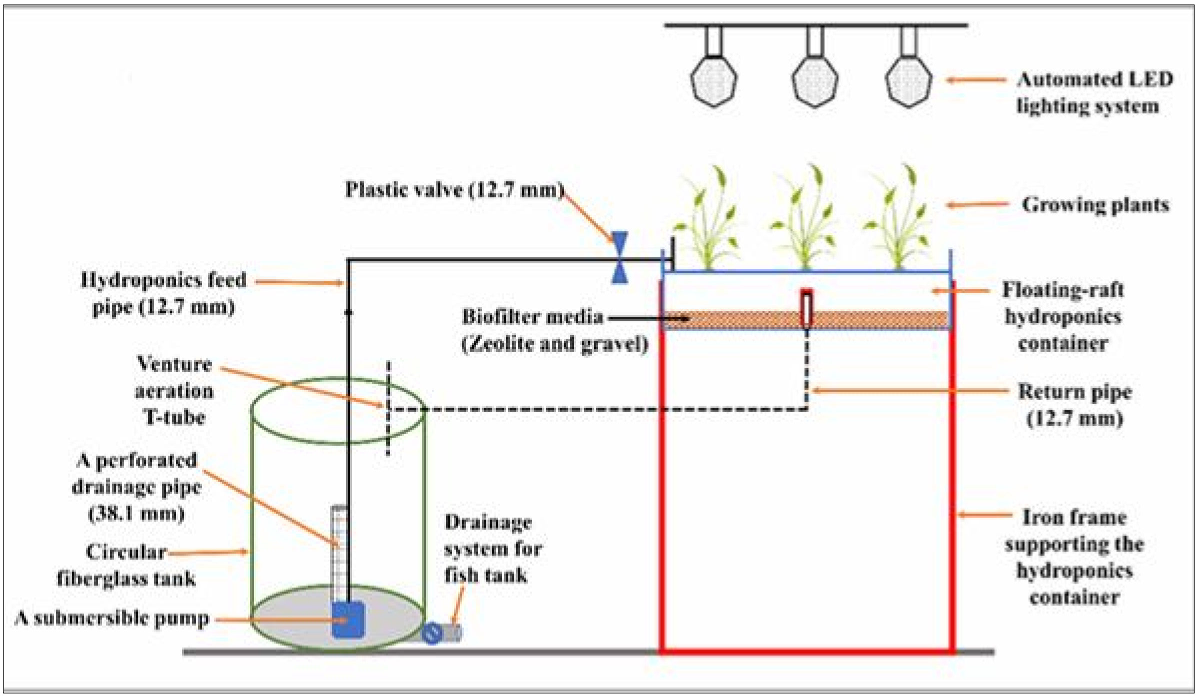

Figure 1. A schematic diagram illustrates the design of aquaponics system components, used in the experiment.

Figure 2. Photos show the setup and operation of the aquaponics systems in the Research Building, Fish Farming and Technology Institute, Suez Canal University, Ismailia. A-C: twelve aquaponics units were operated using four medicinal plants, besides three tanks, as a traditional fish nursery system, D: water recirculation system, and E: automated LED lighting system, and plants are grown in the hydroponics container during the operation of the aquaponics system.

Aeration system. Aeration tubes (high diffuser hose/nano rubber) were purchased from Jiangyin Baichuan Aeration Equipment Co. Ltd, China. A circle aeration tube with the 30-cm diameter was used in the fish tank which located at 60-cm from the bottom end and connected with the central greenhouse supplier (12.7-mm PVC pipe, with a valve) of the compressed air system. Besides, water returns to the fish tank with gravity via 25.4-mm PVC pipe ended with developed venture aeration T-tube, owing to maintaining of the favorable level of water dissolved oxygen in the fish tank (> 6 mg L^{-1}). On the other hand, two airstones (120 mm × 20 mm) connected through 16-mm pipes with the central greenhouse supplier of the compressed air system were used in each floating-raft hydroponics unit.

Automated LED lighting system. Three LED white lamps (11.5 Watts, 1200 lumens, Venus Co. LTD, Egypt) were located at 0.7-meter above hydroponics Styrofoam (Lennard & Leonard 2006) to maintain the optimal illumination for the growing plants. Specifically, the estimated intensity of the artificial light above each aquaponic system was 3600 lumens. The LED lighting system was designed for providing an efficient artificial light for growing the plants in the designed aquaponics system. A 12 h of daylight was performed using a time cycle controller.

Aquaponics system operation. A submersible aquarium pump (40 watts and 220-240 Voltage/50Hz, 2.3 m/head, and 1900 L h^{-1}) was purchased from SUNSUN Group Co., LTD, China. In each aquaponics system, water was recirculated using a submersible aquarium pump from the fish tank to the floating-raft hydroponics container through a connecting 12.7-mm PVC pipe with valve, and, then water returned to the fish tank with gravity via 25.4-mm PVC pipe ended with developed venture aeration T-tube. All systems were working appropriately using a time cycle controller to operate the pump for 10 minutes (10 min ON) to recirculate the water in each system every 20 minutes (20 min OF), ensuring appropriate growing of crops and maintaining good water quality.

Experimental design and feeding regime. Five treatments in three replicates per each were performed. Nile tilapia fry with an initial body weight of 0.134 g $fish^{-1}$ was used at a stocking density of 2200 fry m^{-3}. Twelve aquaponics systems were operated for 30 days (May 2018) to evaluate the efficiency of four medicinal plants on water quality, growth performance, feed utilization, economic evaluation and water-use efficiency of Nile tilapia. Rosemary, mint, marjoram, and thyme plants were cultivated at 25 plants/hydroponics unit with fish:medicinal plant ratio of 88:1 (Figure 3).

The previous four aquaponics nursery treatments were compared to a traditional fish nursery system (control, three tanks) using 20% daily water exchange rate. Only 0.5% of rearing water under aquaponics system was replaced daily to remove a significant ratio of the settable solids. Fish feeding was carried out according to the recommendations of Jauncey & Ross (1982) and Rakocy (1999). Unfortunately, the pellet diet (0.5-1 mm) was not available in the Egyptian market during the experimental period. Thus, the researchers obliged to use fine powdered diet containing 30% protein, purchased from Skretting Egypt (https://www.skretting.com/en-EG/). The fish fry was fed at 8-10% of body weights daily for 30 days (May 2018). The daily feeding amount was divided into four meals (at 8:00 AM, 10:00 AM, 12:00 PM and 2:00 PM).

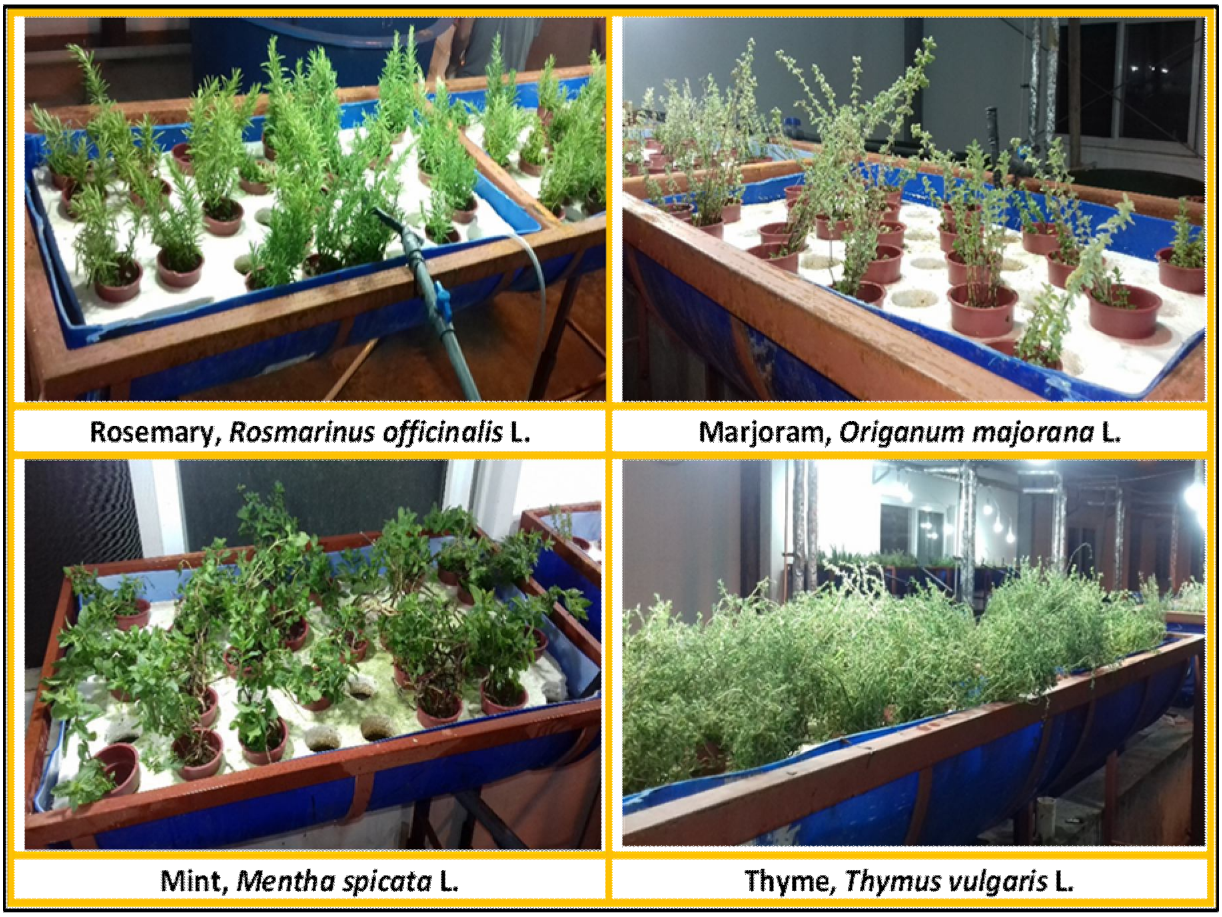

Figure 3. Four medicinal plants, rosemary: *Rosmarinus officinalis* L., mint: *Mentha spicata* L., marjoram: *Origanum majorana* L., and thyme: *Thymus vulgaris* L. plants were cultivated at 25 plants/hydroponics unit with fish: medicinal plant ratio of 88:1.

Sampling and measurements

Water sampling and analytical methods. Water quality indices were determined two times per week from the fish rearing tanks under aquaponics and traditional nursery systems at morning for measuring pH, total ammonia nitrogen (TAN), NH_3, NH_4, NO_3, nitrogen, phosphorus, anions, and cations during the experimental period. The pH and EC values were measured in the collected water samples while ammonia (NH_3) and nitrate (NO_3) were measured at the Soil Fertility Laboratory, Faculty of Agriculture, Suez Canal University, Ismailia, Egypt.

After the filtration of water samples through Whatman paper No.40, Electrical conductivity (EC, dSm^{-1}) and pH of water samples were measured using EC meter model Jenway 3310 and pH meter (bench type Beckman glass electrode pH meter). Calcium and magnesium were measured by volumetric titration with ethylene diamine tetraacetic acid (EDTA) according to the method described by Richards (1954). Sodium and Potassium were measured by a flame photometer (Richards 1954). Nitrate was determined by Devarda's Alloy method according to Page et al (1982). After digestion of water samples, the total nitrogen was determined following the method defined by Page et al (1982). Phosphorus was determined by using spectrophotometer method as described by Page et al (1982). Finally, the nitrate- and ammonium-N were evaluated using a micro Kjeldahl method.

Growth performance indices of medicinal plants. Root and stem lengths were measured on the harvest day of tilapia fry for determining the growth performance of crops in the aquaponics system. The fresh biomasses of shoots and roots were recorded at the end of each experiment. Next, shoots and roots, after measuring the fresh biomasses, were

oven dried at 70ºC until constant weight and then, their dry biomasses were determined (Awad et al 2017). Shoot and root lengths were determined from captured images using ImageJ software (version 1.52g, USA). Images of whole plants with a 30 cm ruler were obtained with an Apple iPhone 7 Plus digital camera (12 MP, f/1.8, 28 mm (wide), 1/3″, OIS, PDAF). The shoot and root lengths were estimated by setting a scale using the ruler beside the plant according to Nunes Maciel et al (2013).
Growth performance and feed utilization efficiency of tilapia fry. At the end of the experiment, fish were harvested, counted, and weighed. The growth performance and feed utilization parameters were determined as follows:

$$\text{Weight gain (g/fish): WG} = W_t - W_0.$$

Where: W_0 = the initial mean weight of fish in grams.
W_t = the final mean weight of fish in grams.

$$\text{Average daily gain (g/fish/day): ADG} = W_t - W_0 / n$$

Where: n = experiment period (days).

$$\text{Specific growth rate (\% day-1): SGR} = 100 \times (\ln W_t - \ln W_0) / \text{days}$$

Where: ln = natural logarithm.

$$\text{Survival rate, (\%)} = 100 \times (\text{final fish number} / \text{initial fish number})$$

$$\text{Feed conversion ratio (FCR)} = \text{feed intake (fish feed quantity)} / \text{wet weight gain}$$

Economic evaluation and water-use efficiency (WUE). Economic evaluation and water-use efficiency indices of the traditional and aquaponics nursery production systems of Nile tilapia fish fry and rosemary plants are performed based on the equations written under the tables of results. Data was calculated based on the price of 0.055$ per m^3 water. Additionally, one US$ = ~ 18 Egyptian pounds (£E) during 2018 was used in the calculations.

***Statistical analysis**.* Data collected on the investigated fish traits (growth performance, feed utilization, economic evaluation, and water-use efficiency), plant traits (growth parameters: shoot/root lengths (cm) and shoot/root fresh and dry weights (g)), and water macro- and micronutrients concentrations were analysed with one-way analysis of variance (ANOVA) using the SPSS version 22 statistical package (SPSS Company Inc., Chicago, IL. USA) to evaluate the differences between the tested treatments. The differences within each experimental treatment were assessed using Duncan's multiple range test at the $p \leq 0.05$ level.

Results

***Growth performance, survival, and feed utilization of tilapia fry**.* Growth performance showed better results for aquaponics-produced fry with medicinal plants (rosemary, mint, thyme, and marjoram plants) as shown in Table 1. Except for thyme plants, there were no significant differences ($p > 0.05$) in the final weight, weight gain, ADG, and SGR of tilapia fry between aquaponics with medicinal plants and the traditional fish rearing system (the control) using 20% daily water exchange rate. Thyme plants in aquaponics improved the growth indices of tilapia fry compared to other medicinal plants and the control treatment significantly ($p \leq 0.05$). Besides, the final number of fry $tank^{-1}$ and survival rate were improved significantly ($p \leq 0.05$) in aquaponics system with rosemary, marjoram, and mint compared with thyme treatment and the control. The highest values were significantly ($p \leq 0.05$) in favor of rosemary treatment compared with the others. Final fish biomass (kg $tank^{-1}$) was increased by 61.4, and 42.1.4% in thyme and rosemary, respectively than that in control. Feed intake and feed conversion ratio were decreased significantly ($p \leq 0.05$) with mint, rosemary, and marjoram plants compared to thyme plants and the control treatment, with the best values in favor of rosemary treatment.

Table 1

Growth performance, survival, and feed utilization of Nile tilapia fry reared under small-scale aquaponics and traditional nursery systems. Data are mean±SEM

Measured traits	*Treatments**				
	Control	*Mint*	*Rosemary*	*Marjoram*	*Thyme*
Final weight ($g\ fish^{-1}$)[2]	1.63 ± 0.10^{b}	1.76 ± 0.05^{b}	1.72 ± 0.08^{b}	1.72 ± 0.07^{b}	2.76 ± 0.07^{a}
Final number (#/tank)[3]	1556.7 ± 34.8^{d}	1693.3 ± 18.6^{c}	2106.7 ± 17.6^{a}	1906.7 ± 34.8^{b}	1490.0 ± 37.9^{d}
Weight gain ($g\ fish^{-1}$)	1.50 ± 0.10^{b}	1.63 ± 0.05^{b}	1.59 ± 0.08^{b}	1.59 ± 0.07^{b}	2.63 ± 0.07^{a}
ADG[4] ($g\ fish^{-1}\ day^{-1}$)	$0.050 \pm .00^{b}$	$0.054 \pm .00^{b}$	$0.053 \pm .00^{b}$	$0.052 \pm .00^{b}$	$0.087 \pm .00^{a}$
SGR[4]	8.32 ± 0.20^{b}	8.58 ± 0.09^{b}	8.49 ± 0.17^{b}	8.49 ± 0.14^{b}	10.08 ± 0.09^{a}
Biomass ($kg\ tank^{-1}$)	2.54 ± 0.17^{d}	2.97 ± 0.06^{c}	3.61 ± 0.15^{b}	3.28 ± 0.18^{bc}	4.10 ± 0.02^{a}
Survival, %	70.76 ± 1.58^{d}	76.97 ± 0.84^{c}	95.76 ± 0.80^{a}	86.67 ± 1.58^{b}	67.73 ± 1.72^{d}
Feed intake ($g\ fish^{-1}$)	1.73 ± 0.08^{b}	1.53 ± 0.02^{c}	1.23 ± 0.01^{d}	1.36 ± 0.03^{d}	2.75 ± 0.07^{a}
FCR[4]	1.16 ± 0.05^{a}	0.94 ± 0.02^{bc}	0.78 ± 0.04^{d}	0.86 ± 0.05^{cd}	1.05 ± 0.01^{ab}

[a-d] Means in the same row sharing the same superscript letter are not significantly different ($p > 0.05$).

Water quality of fish tanks. Except for the last week of the experiment, the designed aquaponics system with intensive fish culture (2200 fry m^{-3}) maintained water quality parameters (e.g., pH, EC, oxygen, and ammonia level) within the favorable limits during the first three weeks, ensuring healthier growth performance of fish fry (Figure 4). In aquaponics with rosemary, mint, thyme, and marjoram plants, pH was sustained at 6.93–7.16 within the recommended range (7 to 7.5), while EC values ranged from 1.1 to 1.45 dSm^{-1}. The water levels of total nitrogen in aquaponics were 23.5, 15.3, 18.8, and 22.9 mg L^{-1} for tilapia tanks with mint, rosemary, marjoram and thyme plants, respectively. The total nitrogen and total phosphorous (P) in aquaponics with medicinal herbs were significantly ($p \leq 0.05$) lower on average by 36.7 and 41.4% than the control treatment, respectively. The total N, NO_3^--N and NH_4^+-N contents in water with rosemary herbs were significantly ($p \leq 0.05$) 2.4-times lower than the control treatment signifying the higher capacity of rosemary to remove the inorganic N and nutrient in aquaponics than other medicinal plants. The NH_3-N content in water for tilapia fry at the stocking density of 2200 fry m^{-3} increased significantly ($p \leq 0.05$) 0.052, 0.087, 0.087, and 0.138, mg L^{-1}, for mint, rosemary, marjoram, and thyme plants, respectively (Figure 5). There were no significant differences ($p \geq 0.05$) in the water contents of cations and anions among aquaponics with medicinal herbs and the traditional fish rearing system (Table 2).

Table 2

Water macro- and micronutrients concentrations in fish rearing (2200 fry m^{-3}) tanks under different medicinal plant species nursed under a small-scale aquaponics system. Data are mean±SEM

Treatment	*Cations meq L^{-1}*				*Anions meq L^{-1}*		
	Ca	*Mg*	*Na*	*K*	*HCO_3*	*Cl*	*SO_4*
Control	2.79 ± 0.12^{a}	4.29 ± 0.38^{a}	5.93 ± 0.48^{a}	1.49 ± 0.09	2.84 ± 0.17^{b}	6.20 ± 0.67^{a}	5.47 ± 0.27^{a}
Mint	2.17 ± 0.13^{b}	3.28 ± 0.34^{ab}	4.33 ± 0.43^{b}	1.20 ± 0.14	3.58 ± 0.21^{a}	3.45 ± 0.59^{b}	3.95 ± 0.29^{b}
Rosemary	2.49 ± 0.17^{ab}	3.40 ± 0.20^{ab}	5.94 ± 0.25^{a}	1.27±=.10	3.75 ± 0.18^{a}	5.05 ± 0.50^{ab}	4.27 ± 0.40^{ab}
Marjoram	2.38 ± 0.15^{ab}	3.13 ± 0.24^{b}	4.77 ± 0.37^{ab}	1.43 ± 0.22	3.25 ± 0.19^{ab}	4.22 ± 0.54^{ab}	4.27 ± 0.47^{ab}
Thyme	2.78 ± 0.13^{a}	3.53 ± 0.49^{ab}	5.96 ± 0.45^{a}	1.30 ± 0.09	3.33 ± 0.19^{ab}	5.84 ± 0.96^{a}	4.39 ± 0.70^{ab}

[a-b] Means in the same column sharing the same superscript letter are not significantly different ($p > 0.05$).

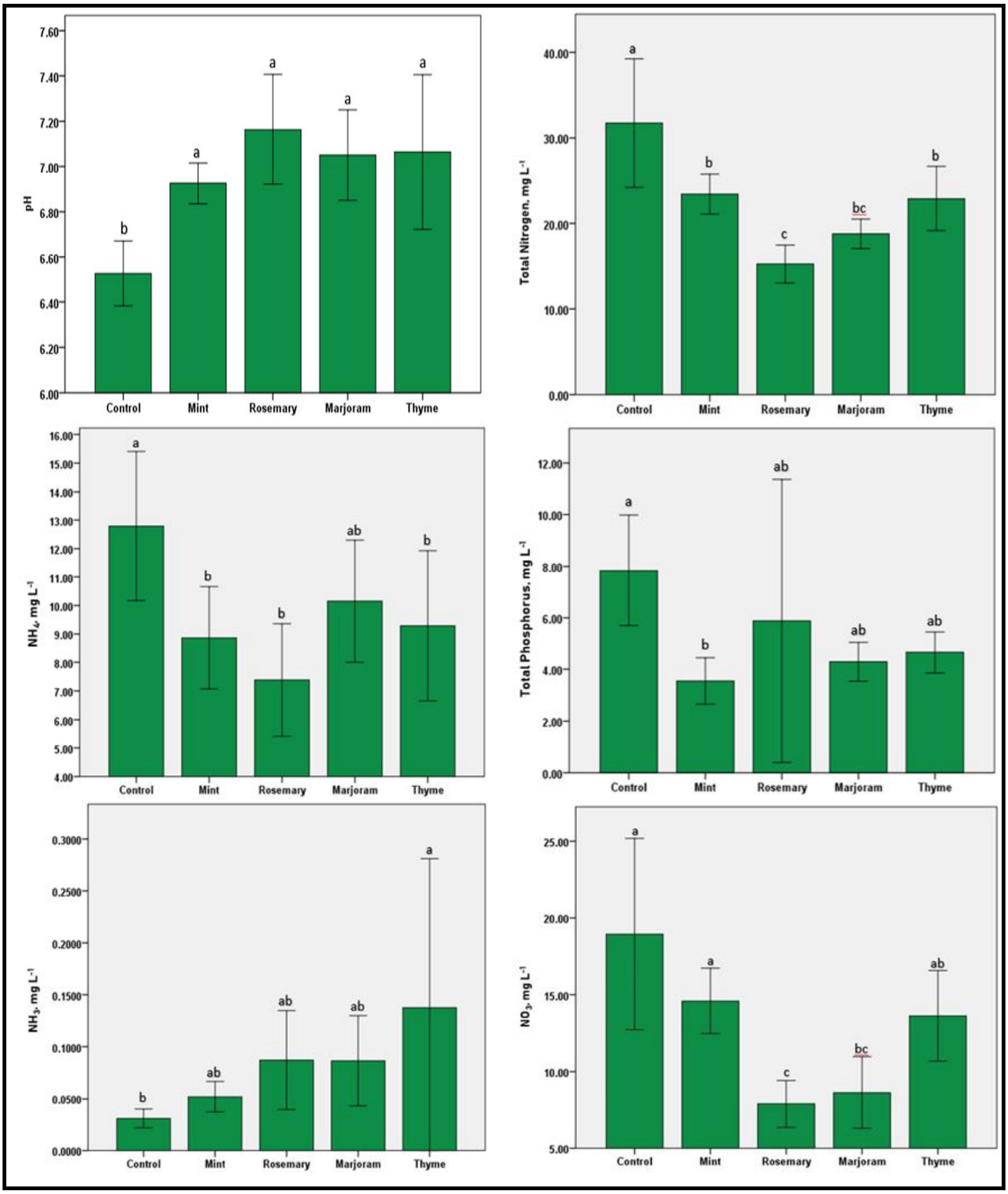

Figure 4. Water quality indices in fish rearing tanks stocked with Nile tilapia fry reared under traditional and small-scale aquaponics systems. Bars characterize the standard error of the mean (n = 3). Bars with the different letters are significantly different at $p \leq 0.05$.

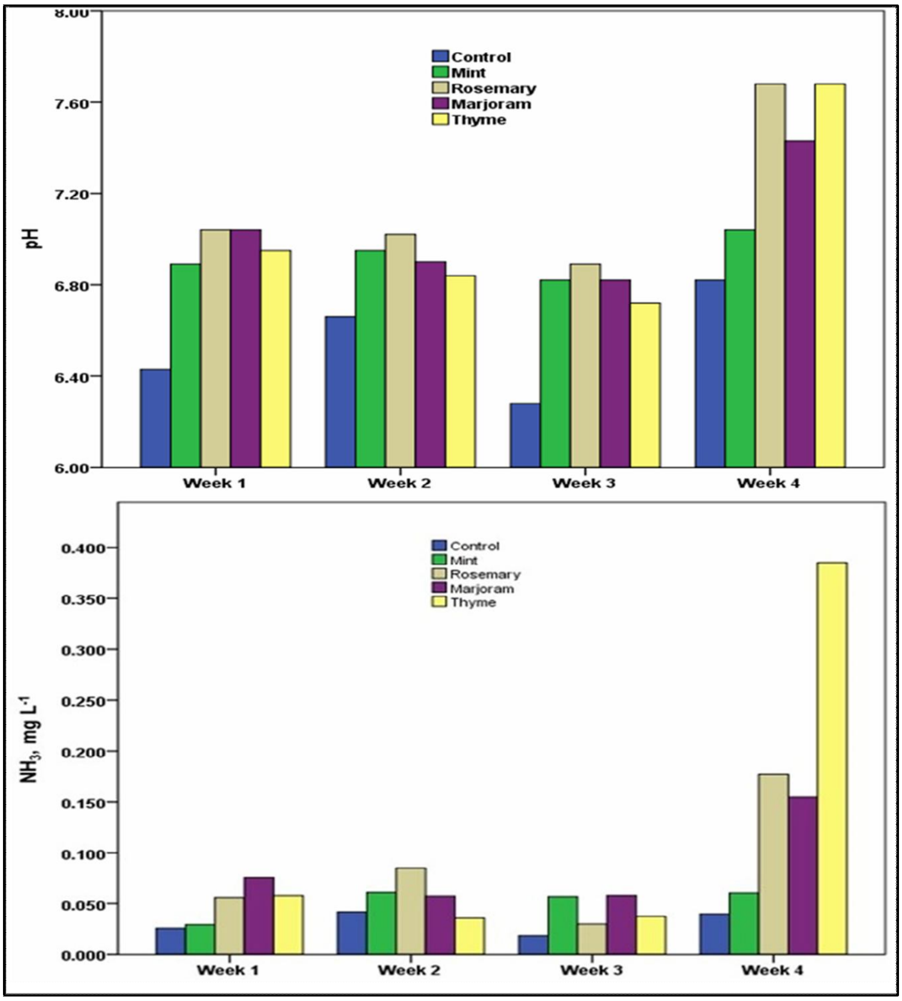

Figure 5. Weekly data of pH and un-ionized ammonia in fish rearing tanks stocked with Nile tilapia fry reared under traditional and small-scale aquaponics nursery systems.

Growth of rosemary and mint plants. Unfortunately, only rosemary and mint plants were continued their growing period for 30 days and provide a good biofiltration system for tilapia fry effluent in the designed aquaponics system during one-month operation of the system. The relatively low growth rate of mint plants and the death of marjoram and thyme plants were occurred during the last week of the experiment because of the forming gel on plant roots from the dissolution of the fine and dissolved solids from the powdered fish diet in water (Figure 6). This was probably because of the significant increase in the size and weights of tilapia fry, daily feeding rate and imbalance the equilibrium between fish density, nitrifying bacteria and the root surface area of marjoram and thyme plants. Growth performance of rosemary plants improved significantly ($p \leq 0.05$) compared to mint plants (Table 3 and Figure 6).

The fish density of 2200 fry m^{-3} increased the fresh and dry shoot biomass of rosemary (g $plant^{-1}$) and Log10 (shoot:root) by 2.3-times and 1.2-times on average higher than that of mint plants, respectively. Besides, rosemary had the highest growth performance as indicated from highest Log10 (shoot:root; 0.59). It is cleared from the results that rosemary plants have a great potential in aquaponics with intensive fish culturing density (2200 fry m^{-3}).

Table 3
Growth performance of rosemary and mint plants with a stocking density of Tilapia fish fry of 2200 fry m-3 in a small-scale aquaponics system

Parameters	*Mint*	*Rosemary*
The initial number of plants	25	25
Final fresh shoot biomass (g plant^{-1})	4.27^{b}	9.87^{a}
Final fresh shoot biomass (g tank^{-1})	106.81^{b}	246.84^{a}
Final fresh root biomass (g plant^{-1})	11.68^{*,a}	5.66^{b}
Final fresh root biomass (g tank^{-1})	292.08^{*,a}	141.58^{b}
Final fresh plant biomass (g plant^{-1})	15.96^{a}	15.54^{a}
Final fresh plant biomass (g tank^{-1})	398.89^{a}	388.42^{a}
Final dry shoot biomass (g plant^{-1})	2.31^{b}	5.33^{a}
Final dry shoot biomass (g tank^{-1})	57.68^{b}	133.29^{a}
Final dry root biomass (g plant^{-1})	6.31^{*,a}	3.06^{b}
Final dry root biomass (g tank^{-1})	157.73^{*,a}	76.45^{b}
Final dry plant biomass (g plant^{-1})	8.62^{a}	8.39^{a}
Final dry plant biomass (g tank^{-1})	215.40^{a}	209.75^{a}
Log10 (shoot:root)	-0.49	0.59

* Fresh and dry biomass of mint roots plus rhizomes were determined for mint plants; $^{a-b}$ Means in the same row sharing the same superscript letter are not significantly different (p > 0.05).

Figure 6. The formation of gel on thyme (left) and marjoram (right) roots due to the dissolution of finely powdered diet and sedimentation of fish feces after the inhibition of nitrification process of the aquaponics system during the last week of the experiment.

Economic evaluation and water-use efficiency. An economic evaluation of the traditional and aquaponics nursery production systems of Nile tilapia fry and rosemary plants is presented in Table 4. Total variable costs (TVCs) and total production cost of one production run aquaponically were 1.8-times higher than the traditional nursery system. In contrast, freshwater cost (FC)/total production of aquaponics nursery system was 9.3-times lower than the traditional nursery system. Total revenue from aquaponic nursery system (fish + plants) was 2-folds higher than that of the traditional nursery system. Benefit-Cost Ratio (BCR) for aquaponic nursery system was 1.7-times higher than the traditional nursery system. The fish number and biomass per m^3 were 7.1-times higher compared to the traditional nursery system. Furthermore, financial water-use efficiency for aquaponic nursery system (fish + plants) was 16-times higher than that in the traditional nursery system (Table 5). It is evident from the economic evaluation and water-use efficiency that aquaponic system is a zero-water exchangeable system with twice economic net profit compared to the traditional nursery system.

Table 4

Economic analysis and profitability of the traditional and aquaponics nursery systems of Nile tilapia fry and rosemary, *Rosmarinus officinalis* plants

Economic and financial criteria (per nursery unit (NU) for one production run)	*Unit (§)*	*Treatments*		*Differentiation (%)*[17]
		Traditional	*Aquaponics*	
Investment cost (IC)[1]	$/NU	556	644	115.8
Capital cost (CC)[2]	$/NU	3.47	6.53	188.2
	Variable costs			
Mono-sex tilapia fry (TF)	$/NU	2.78	2.78	100
Artificial feed (AF)[3]	$/NU	1.643	1.581	96.2
Labor (LC)	$/NU	5.56	7.56	136.0
Electricity (EC)[4]	$/NU	0.444	1.222	275.2
Freshwater cost (FC)[5]	$/NU	0.333	0.0639	19.2
Plants (PC)	$/NU	0	3.5	-
Other variable costs (OVC)	$/NU	1	4	400
Total variable costs per NU (TVC1)[6]	$/NU	11.761	20.707	176.1
Total variable costs per fry (TVC2)[7]	$/1000 fry	7.554	9.828	130.1
	Total production cost (TPC)			
Total production cost per NU (TPC1)[8]	$/NU	15.231	27.237	178.8
Total production cost per fry (TPC2)[9]	$/1000 fry	9.782	12.927	132.2
Total variable costs /total production cost, (TVC1 /TPC1)	%/NU	77.218	76.025	98.5
Freshwater cost (FC)/total variable costs per NU (TVC1)	%/NU	2.834	0.309	10.9
Electricity and fuel (EF)/total variable costs per NU (TVC1)	%/NU	3.779	5.902	156.2
	Total revenue, $			
Total revenue of fish (TRf)	$/NU	19.463	26.338	135.3
Total revenue of plants (TRp)	$/NU	0.0	13.889	-
Total revenue (fish and plants) (TR)[10]	$/NU	19.463	40.226	206.7
Gross margin (GM)[11]	$/NU	7.701	19.519	253.5
	Net profit, $			
Net profit per NU (NPPT)[12]	$/NU	4.231	12.989	307.0
Net profit per 1000 fry (NPPF)[13]	$/1000 fry	2.718	6.165	226.8
Benefit-cost ratio (BCR)[14]	%	27.78	47.69	171.7
Internal rate of return (IRR)[15]	%	0.761	2.017	265.0
Payback period (PP)[16]	year	2.190	0.826	37.7

1 - IC = investment cost of one unit of NU (including all supporting units; aeration, water pumps, etc.); 2 - CC = capital cost (annual depreciation) was calculated based on 20 years' life span = investment cost/20yrs and 8 fish production runs and 6 plant production runs; 3 - AF = quantity of diets (kg) * average price (0.61 $/kg); 4 - EC = (electricity usage (KW)* average price (1$/kw) during experimental period; 5 - FC = total cubec meters of water * average price (0.055$/$m^3$) during experimental period; 6 - TVC1 = (TF+ AF+LC+EC+FC+PC+OVC); 7 - TVC2 = TVC1/total number of produced fry per NU (TNPF); 8 - TPC1 = TVC1 + CC; 9 - TPC2 = TPC1 / TNPF; 10 - total revenue (TR) = [(TNPF * fish price (12.5$/1000 fry) + (plant number*0.56$/plant)]; 11 - gross margin (GM) = TR-TVC1; 12 - NPPT = TR – TPC1; 13 - NPFF = net profit per 1000 fry = NPPT/TNPF; 14 - BCR = benefit-cost ratio = 100*(NPPT/TPC1); 15 - IRR = internal rate of return (IRR) - % = 100*(NPPT /IC); 16 - payback period (PP) – years = (IC / (NPPT*8)); based on how many productions run per year; 17 - differentiation (%) = (aquaponics/traditional) *100.

Table 5

Technical and financial water-use efficiency (WUE) of the traditional and aquaponics nursery systems of Nile tilapia fry and rosemary, *Rosmarinus officinalis* plants

Water-use efficiency criteria	*Unit*	*Treatments*		*Differentiation (%)*[3]
		Traditional	*Aquaponics*	
Fish number per m^3 (1a)	fry m^{-3} water	259.5	1832.2	706.1
Fish biomass per m^3 (1b)	kg m^{-3} water	0.423	2.986	705.9
Plant number per m^3 (1c)	fry m^{-3} water	-	21.74	-
Plant biomass per m^3(1d)	kg m^{-3} water	-	0.337	-
Financial Water-Use Efficiency (WUEf)[2]	US $ m^{-3}	0.705	11.295	1602.1

1a - technical water-use efficiency (WUEt) = (total number of produced fry per NU /total volume of used freshwater, m^3); 1b - technical water-use efficiency (WUEt) = (fry biomass per NU /total volume of used freshwater, m^3); 1c - technical water-use efficiency (WUEt) = (total number of produced plants per NU/total volume of used freshwater, m^3); 1d - technical water-use efficiency (WUEt) = (plant biomass per NU /total volume of used freshwater, m^3); 2 - financial water-use efficiency (WUEf) = (net income per NU / total volume of used freshwater, m^3); 3 - differentiation (%) = (aquaponics/traditional) *100.

Discussion. The nutrient-rich water effluent in the designed aquaponics system led to the growth of medicinal plants with Nile tilapia fish fry at a density of 2200 fish m^{-3}. The growth of medicinal herbs was enhanced because of the uptake of water NH_4-N besides NO_3-N which is generated by nitrifying bacteria in the biofilter media, hydroponics substrate, and the surface of plant roots. Biofiltration of water by plant roots enhanced the growth of fish fry (final biomass, weight gain, SGR), and this agreed with the findings stated in several studies (Palm et al 2014; Hundley et al 2018). The production of marjoram herbs using aquaponics was successfully operated with Nile tilapia fingerlings (initial body weight of 6.96 g $fish^{-1}$) at culturing density of 500 fish m^{-3}, contributing to a 43% weight gain of fish as reported by Hundley et al (2018). Higher fish biomass in thyme treatment reduced the survival rate of fish. This is agreeing with Rayhan et al (2018), who stated that the higher the stocking density (fish biomass), the lower the survival rate. Overcrowding can cause physical disturbance stress, besides poor water quality which may lead to disease outbreaks as a result of the competition for feeding (Somerville et al 2014) or low survival. The FCR describes how efficiently a fish turns its feed into edible meat. Obtained FCR data from the present study were reasonable compared with others (Effendi et al 2017).

It is evident from water physicochemical characteristics that there was a balance for meeting the necessities of biofiltration of toxic ammonia and the nutritional requirements of plants during the first three weeks of the experiment (Timmons & Ebeling 2007). Only the integration between rosemary and mint plants to a fish fry with ratio 1:80 was only implicitly improved during the last week of the experiment, contributing to the functioning of the hydroponics and tilapia fry culture as one unit in a relatively sustainable way. In contrast, water quality was relatively reduced but remained safe for fish in the aquaponics systems with thyme and marjoram plants. In contrast, marjoram and thyme plants at the last week of the experiment exposured to the stress of high-water pH because of the dissolution of finely powdered diet and sedimentation of fish feces in water forming a gel which precipitated on plant roots and limited the growth of plants and the nitrifying bacteria.

It is revealed that TAN in the finely powdered aquaponics system was higher than the safe threshold of 5 mg L^{-1} as confirmed in a study by Tyson et al (2007), contributing to the lower growth of tilapia fry substantially. However, they revealed that keeping water pH below 7.5 avoided the accumulation of toxic nitrite in the designed aquaponics system. Additionally, the effective aeration system (maintained at ~6 mg L^{-1} dissolved oxygen) in the designed aquaponics controlled the overall nitrification process in water, ensuring no considerable amount of nitrite accumulation (Rakocy et al 2006; Rakocy 2012). It was evident from the results that aquaponics was operated satisfactory using tilapia fry with only the root systems of rosemary and mint plants. Rosemary is well-matched to the designed aquaponics systems as rosemary plants have medium nutritional requirements (Diver 2006). For instance, mint plants were successfully produced using floating rafts in the aquaponics system with common carp for 30 days, and the removal rates of TAN and NO_3^- were 69% and 68%, respectively as reported in a study by Shete et al (2017). Also, Tyson et al (2011) concluded that the aquaponics' plants can absorb NO_3^- and NH_4^+ as N needed by plants. Crayfish cultivated aquaponically with water spinach enhanced water quality, through the elimination of 81% NH_3, 33% NO_3, and 89% PO_4 (Effendi et al 2015). They also revealed that biofilter-media and hydroponic substrates were most active on the growth performance of fish and water quality at the end of the experiment, owing to better nutrient removal and water quality. Furthermore, the gravels + zeolite act as biofilter with the highest performance due to the excellent aeration system in the designed aquaponics as explained by Al-Hafedh et al (2008).

Our findings have confirmed the results of Al-Hafedh et al (2008) who illustrated that floating rafts in the aquaponics system could provide enough biofiltration when plant cultivation area is sized appropriately. From a practical viewpoint, the highest water pH up to 8.2 during the last week in the aquaponics with thyme plants might be raised the toxicity of unionized ammonia in the system. This was probably the reason for lower nutrient uptake by thyme (NH_3-N was ~0.4 mg L^{-1}), and marjoram plants (NH_3-N was

~0.2 mg L^{-1}) besides higher pH inhibited the overall nitrification process in water as indicated from no more elevated amount of nitrate accumulation compared to NH_4-N contents (Brinkman et al 2009).

The safe level of unionized ammonia is 0.42 mg L^{-1} was the main reason for no severe mortality in fish fry in the designed aquaponics (Benli & Koksal 2005). The contents of NO_3^--N, NH_3-N, and TAN in aquaponics and the control treatment were within safe ranges, with desirable lower pH except for thyme and marjoram at the last week of the experiment. The failure of the nitrification process in aquaponics with thyme and marjoram plant was due to the higher water pH because of the imbalance between the fish density, daily feeding rate and surface area of plant roots. Higher water pH was the primary mechanism of the lower performance of the plants and nitrifying bacteria to remove the ammonia during the last week of the experiment. Additionally, the dissolution of finely powdered diet and sedimentation of fish feces in aquaponics with thyme and marjoram plants formed a gel which was precipitated on plant roots and limited the growth of plants and the nitrifying bacteria. The highest removal rate (54.7%) of phosphorus occurred with mint, while the overall average of aquaponics plants was 41.4% compared with the control. This is in agreement with Cerozi & Fitzsimmons (2017) who concluded that the assimilation of phosphorus in the fish and plant tissues reached 71.7% of the total P input, pointing out high P utilization. Also, Li et al (2013) stated that phosphorus (P) is accumulated in plant root tissues. The removal efficiency of phosphorus occurred continuously (Effendi et al 2017). Therefore, aquaponics is an excellent tool for recycling phosphorus yielding some high-quality, valuable products.

The successful operation of the aquaponics system was probably due to three reasons. First, biofilter medium and hydroponics substrate (zeolite plus gravels) removed the toxic unionized ammonia through the nitrification process. Specifically, nitrifying bacteria transformed 93-96% of poisonous NH_3-N into non-toxic NO_3-N in biofilter as reported in Goddek et al (2015), Rakocy (2012) and Timmons & Ebeling (2007). The biofilm formation on the surface of the zeolite substrate avoids the saturation of NH_3-N on its surface by converting ammonium to nitrate microbially (Chang et al 2009). Also, the NH_3-N removed on zeolite media through nitrification and ion exchange processes. It is clear from the results that natural zeolite is a useful media for the removal of NH_3-N from fish effluent (Aly et al 2016; Abdel-Rahim 2019). Second, maintaining water pH below 7.5 is being recommended to avoid the accumulation of toxic nitrite (Timmons & Ebeling 2007). Third, the effective aeration system in the designed aquaponics system controlled the overall nitrification process in water, ensuring no considerable amount of nitrite accumulation (Rakocy et al 2006; Rakocy 2012).

Freshwater consumption is the absolute minimum needed to grow the plants, and only a negligible amount of water is lost for evaporation from the soil-less media. Overall, aquaponics uses less than 10 percent of the water needed to grow the same plant in soil. Thus, soil-less cultivation has excellent potential to allow production where water is scarce or expensive. The demand for energy and electricity are the major limiting components of small-scale aquaponics (Somerville et al 2014). Therefore, commercial aquaponics in temperate to warm climates was to be more profitable with 4-times compared with those in colder climates (Love et al 2015). It is fortunate that the cost of heating could not be a constraint during the most month of the year. The net profit achieved in this study is in agreement with the findings of Tokunaga et al (2015) who stated that the sales price for tilapia in some regions is profitable, and they speculate that aquaponics would be more beneficial than hydroponics given the additional profit from fish.

Freshwater is a precious, limited resource. Many human activities starting with drinking water compete with other vital ones including agriculture, industry, recreation, and fish production. Therefore, water-use efficiency (WUE) is a critical vegetation criterion which emphasized the maximum utilization of freshwater resources at the leaf to global scales (Beer et al 2009; Knauer et al 2018) and should also be used in aquaculture. According to the data of this study, each cubic meter of freshwater used in aquaponics unit with rosemary produced 1832.2 fingerlings of tilapia and raised profitability to 11.295 US$ compared with 159.5 fingerlings and 0.705 US$ under the traditional system, in addition to the second product of rosemary. This rationalization of water consumption (1/40) undoubtedly will serve and support other vital productive sectors without adversely affecting the strategic global productive plans for the aquaculture sector. Unfortunately, there is no data available for WUE in aquaponics, except what stated by Suhl et al (2016) that the freshwater-use efficiency was increased using aquaponics compared with hydroponics for intensive production of tomato. However, another study performed by Abdul-Rahman et al (2011) concerning improving water-use efficiency in semi-arid regions through integrated aquaculture/agriculture concluded that water-use efficiency in terms of fish biomass per cubic meter was 0.22 kg m^{-3} (priced with 1.54 \$ m^{-3}) compared with 2.986 kg m^{-3} (rated with 11.3 \$ m^{-3}) of the current study.

Conclusions. It is evident from the results that aquaponics was operated in a realistic way using tilapia fry at 2200 fry m-3, but the cultivation area of rosemary plants needs to be determined correctly. The ratio of rosemary plants to tilapia fry should be adjusted to maintain water quality parameters under the aquaponics treatments within the acceptable levels of tilapia fry despite the reduction in water usage by 40-folds of the control. In brief, it can be concluded from the findings of the current study that cultivating the medicinal and aromatic herbs in an aquaponics system is essential for tilapia hatchery to meet the challenges of water shortage in arid and semiarid regions and enhance the efficiency of the available freshwater sources.

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