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Production efficiency of green beans integrated with tilapia in a circular farming system of media-filled aquaponics

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Abstract

Aim of study: To evaluate the biomass production of green bean (*Phaseolus vulgaris*) in a media-filled aquaponics system together with Genetically Improved Farmed Tilapia, GIFT (*Oreochromis niloticus*).

Area of study: Kota Kinabalu, Sabah (Malaysia).

Material and methods: The experiment involved modulating and optimizing the density of extractive species (plants) in the hydroponic tank (55 cm × 35 cm). Five treatments were carried out: T0 (control-without plant), T2 (2 plants), T4 (4 plants), T8 (8 plants), T12 (12 plants) where the stocking density of GIFT was 30 tails (identical in all the treatments). Water volume in each treatment was 800 L and the experimental set up was closed recirculating type. The trials were carried out over a period of 90 days.

Main results: Growth of the GIFT was not affected by the presence of green bean or by manipulation of the stocking density. Treatment T4 yielded significantly higher biomass production of green beans (1556.4 ± 88.9 g), compared to T2 (1083.6 ± 86.9 g), T8 (404.6 ± 47.9 g), and T12 (401.8 ± 98.1 g). There were noticeable fluctuations in the concentrations of NH₃-N (ammonia), NO₂-N (nitrite), NO₃-N (nitrate) and PO₄-P (phosphate) over the experimental period that indicated the process of nitrification and absorption of nutrients.

Research highlights: The nitrogenous waste produced by the fish supported the biomass of the green beans in the aquaponics system and the waste uptake of this extractive species is effective enough for reuse of the water for rearing of GIFT.

Additional key words: integrated aquaculture; circularity; nutrient cascading; system homeostasis.

Abbreviations used: DGR (Daily Growth Rate); DO (Dissolved Oxygen); FCR (Feed Conversion Ratio); GIFT (Genetically Improved Farmed Tilapia); IMTA (Integrated Multi-Trophic Aquaculture); SGR (Specific Growth Rate).

Authors' contributions: All the authors have contributed to this research. Implementation of experimental work: SS. Experimental designing and obtaining funds: AE. Infrastructure development and maintenance: SRMS. Data interpretation, writing and overall supervising of research progress: SM.

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Introduction

In recent years the aquaponics has rapidly gained interest as a method of sustainable production of aquatic food rich in protein, fiber, minerals and vitamins (Liang & Chien, 2013). The integration of aquatic animals and plants symbiotically in closed aquaculture system that recirculates and reuses the water and achieves nutrient cascading is resource-efficient and environment-friend-

ly (Liang & Chien, 2015; Anderson *et al.*, 2019; Lu *et al.*, 2019; Yep & Zheng, 2019). Its operation on the circular bioeconomy concept offers a range of options for a wider use. The combination of aquatic animals (fish, lobster, crabs, prawns, crayfish as well as bivalve, clams, mussels, sea cucumbers) with vegetables, fruits, herbs and flowers can be adapted in various ways according to prevailing situations (Love *et al.*, 2015; Takunga *et al.*, 2015). Aquaponics is now positioned as among those

aquatic farming systems that can address sustainability requirements that are becoming increasingly important for enhancing food supplies to meet the projected demands (Tidwell, 2012; Silva *et al.*, 2017; Knaus *et al.*, 2018; Maucieri *et al.*, 2019).

Previous research done by Estim *et al.* (2018) has shown the suitability of cultivating green beans (*Phaseolus vulgaris*) with Nile tilapia in aquaponics systems. This method of farming lowered the operational cost by producing fish and plants in one harvesting time and system, reducing the labor inputs and minimizing the ecological footprint. The authors emphasized the soilless nature of the farming system that can be practiced even in limited spaces in the backyard in addition to large-scale farming units. In a recent publication, Ferranti (2019) has discussed the viability of aquaponics in yielding organic food for human health, income for small-scale farmers and environmental compatibility. Earlier, Mustafa & Shapawi (2015), Mustafa *et al.* (2018, 2019), Mustafa & Estim (2019) and Shaleh *et al.* (2019) have extensively reviewed the relevant literature and elaborated the significance of such aquatic farming systems in meeting the goals of sustainable development.

Green beans are in demand in the food market because of the good taste, the crunchiness and high nutrient contents such as protein, phosphorus, zinc, iron, vitamin B1 and fiber (Salinas-Ramirez *et al.*, 2011; Satriani *et al.*, 2015; Darkwa *et al.*, 2016). Their use in extracting protein concentrates for the so-called 'plant meat' is also receiving a great deal of attention. This plant is easily grown in an environment where light is abundant, and nutrients are available to support growth of leaves and pods. Besides, green bean is among the important legumes consumed worldwide and is known for an excellent ability to fix nitrogen for biomass production (Gencoglan *et al.*, 2006).

There is a limited amount of scientific data on the optimum conditions for production of green beans in the aquaponic systems. This knowledge gap should be filled because the integrated production of this high-value food is important as much as it not only influences the production efficiency but also the water quality management in the system that regulates nutrient dynamics. Factors affecting the growth and production are general environmental conditions, availability of nutrients and system design among others (Grassbaugh & Bennett, 1998).

In this context, the optimization of stocking density of extractor species (plant) is the most important factor in production management as it affects the cost and quality of the desired crop (Caliskan *et al.*, 2009; Lashkari *et al.*, 2011; Nik, *et al.*, 2011).

As for the target species of fish, the genetically improved farmed tilapia (GIFT), is among the fastest-growing freshwater fish species in aquaculture worldwide. It is known to have superior growth performance compared to other tilapia strains, is easy to breed, has a remarka-

ble tolerance to water quality variations and is known for high disease resistance (Hussain, 2009; Long *et al.*, 2015; Haque *et al.*, 2016; Qiang *et al.*, 2018; Tian *et al.*, 2018). The fish can grow at a fast rate even under crowded conditions with good biomass production in integrated systems (Egna and Boyd, 1997). High survival rate is also attributed to its flexible feeding habits, where diet comprises suspended particulate as well as benthic matter. Commercial pellets are generally used to maximize the growth of the tilapia so as to lessen the culture period. Rakocy *et al.* (2014) stated that only 25- 30% of the feed is converted to reusable energy while the balance is excreted as a waste and some of the contained nutrients leach out in the water. This triggers the microbial action for chemical transformation of the nutrients. The ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) work in conjunction to oxidize ammonia to nitrite, and nitrite to nitrate, respectively. Nitrate is the least toxic of the nitrogenous fractions in the aquaculture system and is used by plants for their growth (Anderson *et al.*, 2019).

This study is intended to generate information on the suitable stocking density of green beans in the media-filled aquaponics integrated with GIFT in a uniquely designed culture module. Additional research backed by an outreach to the farmers will help communicate the best practices to the farming communities. Selection of compatible species of fish and plant which fetch good price in the market and can be raised in healthy condition will demonstrate the profitability of aquaponics and its emergence as a mainstream form agriculture or aquaculture. For small-scale farmers, cost, market and operational feasibility are important. A sustained research on these key considerations can support translation of the aquaponics experimental trials into commercial-scale practices.

Materials and methods

The experiment was carried out at the Integrated Multi-trophic Aquaculture (IMTA) Experimental Area, Borneo Marine Research Institute, Universiti Malaysia Sabah, over a period of 90 days. The production unit area was covered with a transparent roof and an additional thin black sheet that allowed 50% penetration of sunlight. The system was supplied with electricity for the operation of water pump and provided access to freshwater.

Description of the integrated aquaponics system

Design of the aquaponics system used in this study is shown in Fig. 1. It was a closed recirculating system consisting of a black-circular fish tank, a filter tank with two outlets, two plant tanks (each with one outlet) and a submersible water pump (25 watts). The system was

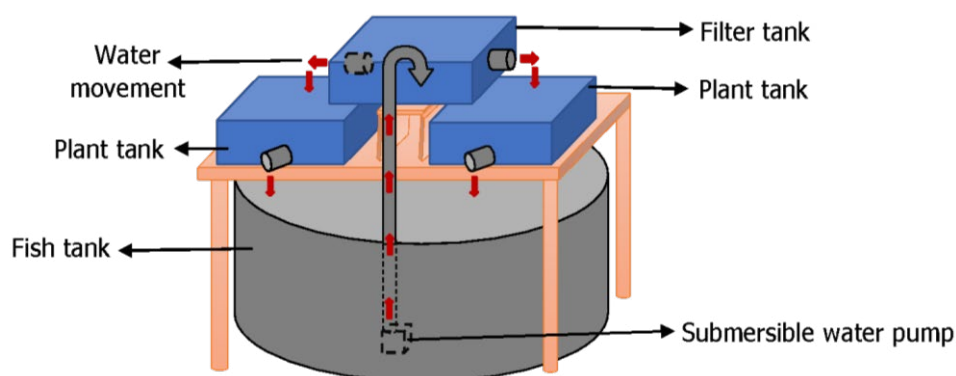


Figure 1. Experimental design of media-filled aquaponics system.

equipped with the aeration facility. Water flow from the fish-holding tank (750 L) to filter tanks (25 L) was regulated. The filter tanks consisted of substrates for biological filters in the form of sponges and gravel. From there the water moved by gravity to the plant tank (15 L) before finally going back to the fish tank. This recycling continued throughout the experiment. Aeration was provided by air stones connected to the air blower to supply sufficient dissolved oxygen to the captive fish in the rearing tank. The loss of water from evaporation was monitored and replenished by aerated water in the storage tanks. The vertical scale in the culture tank helped in measuring the water volume and replenishing the evaporated amount.

Before starting the experiment, the production unit was washed with water, checked for any leakage and allowed to dry. Dechlorinated freshwater was then allowed into the system for the experiment. Routine work included bottom cleaning by sucking up the solid waste in the fish tank. Synthetic sponge pieces were placed on the top of the filter tank to trap large solid waste to prevent blockage of the pipes. There was no water renewal except for the addition of water to replace the volume lost due to evaporation. The water flow rate in this study was 1.6 L/min as

suggested by Endut *et al.* (2011). A ball valve was placed at the end of polyvinyl chloride (PVC) pipe connected to submersible water pump attached to the fish tank to regulate the water flow.

Experimental procedure

The experiment was conducted in the assembly of facilities arranged for aquaponics (Fig. 2). Five treatments involved in this study were: aquaponic system without plant to act as control (T0), and units with 2 (T2), 4 (T4), 8 (T8) and 12 (T12) stocked plants. The stocking density of GIFT was maintained the same in all the treatments. Thirty tails of GIFT with an initial average weight $22\text{g} \pm 1.40\text{ g}$ and size 7.6 cm were placed randomly in the five rearing facilities in triplicate. Before commencement of the trials, the fish were acclimatized for two weeks. During this period, they were fed twice daily at the rate of 6% of body weight. The feed was in the form of commercially available tilapia starter pellets (Leong Hup Feed Mill Malaysia Sdn. Bhd.) comprising 34% protein, 5% lipid and 12% moisture. During the 90-day experimental



Figure 2. (A) Tilapia holding area of the aquaponics system. (B) Green beans emerging from the grow-bed area of the aquaponics system.

period, the feeding and other conditions of captivity were similar.

Measurement of GIFT growth and green bean (*Phaseolus vulgaris*) yield

The growth and survival of GIFT were monitored by observing body weight gain (g), specific growth rate (SGR), daily growth rate (DGR), survival rate (%) and feed conversion ratio (FCR). The following formulae were used to analyze the data:

$$\text{Body weight gain} = W_2 - W_1$$

$$\text{SGR} = \left[\frac{\ln W_2 - \ln W_1}{T_1} \right] \times 100$$

$$\text{Survival rate (\%)} = \left[\frac{\text{No. of fish at the end of the experiment}}{\text{No. of fish at the start of the experiment}} \right] \times 100$$

$$\text{FCR} = \text{Total feed intake (g)} / \text{weight gain of fish (g)}$$

$$\text{DGR} = (W_2 - W_1) / T_1 \text{ (g/fish/day)}$$

where W_1 = initial body weight (g), W_2 = final weight gain (g), and T_1 = duration of culture period (days).

As for the growth of green beans, parameters selected were: average total yield (g), average pod yield (g), length of roots (cm), length of leaves (cm), number of pods produced and average total length of pods (cm) for each treatment. Seeds were planted in the soil for germination. After a week, all the seeds were transferred to hydroponic tank containing a bed of washed gravel. The first 45-days were the initial phase to allow growth and multiplication of leaves and shoots, and thereafter the formation of green beans started.

The selection of stocking biomass of green beans was aided by the preliminary work (Mustafa *et al.*, 2019) preceding these experimental trials. Starting with 2 plants when control set was without any plant and increasing the number to 12 was appropriate as much as it was rational.

Measurement of water quality and analysis of nutrient concentrations

Sampling of water for quality analysis was done every 2 weeks to determine the concentration of ammonia ($\text{NH}_3\text{-N}$) using the Hach Ammonia Low-Range Standard Method 10023. Nitrite ($\text{NO}_2\text{-N}$) concentration was also determined by the Hach Low-Range Standard Method 8192. Nitrate ($\text{NO}_3\text{-N}$) concentration was determined using Hach Nitrate High-Range Standard Method 8093 while for phosphate ($\text{PO}_4\text{-P}$) the Hach Standard Method 8048 was followed. These water nutrient concentrations were analyzed by the help of UNICO 2100 spectrophotometer.

Measurements of dissolved oxygen (DO), pH and temperature ($^{\circ}\text{C}$) were performed using the YSI multi-probe meter (YSI 550A model). For rest of the analysis the wa-

ter samples were taken to the laboratory and processed according to the techniques suggested by Parsons *et al.* (1984).

Statistical analysis

All the data obtained were analyzed with SPSS (statistical package for social sciences) vers. 21 (SPSS Inc. USA) and Microsoft Excel 2015 for data recording. Data collected was subjected to one-way ANOVA to test the significance of differences, if any, at $p < 0.05$ between all the treatments. Significant difference at 0.05 level was compared with Shapiro-Wilk test and the differences between the mean values by Tukey HSD Test. The variability in the unpaired data was recorded as mean $\pm$ standard error (SE).

The experimental period of 90 days allowed the production phases to be monitored, with the first 40 days for proliferation of branches and leaves, followed by a second phase (41-45 days) marked by the formation of white-purplish flowers that eventually turned into pods while growth continued. Subsequently, after 45 days, over a period of 30 days, green bean harvesting was carried out before the plant completed its normal life span. These were the reasons for experimental period of 90-days, that allowed completion of the growth cycle of the green beans and determination of the biomass production of the green beans as well as that of the GIFT.

Results

GIFT growth performance

Data pertaining to indicators of growth performance of GIFT, namely SGR, DGR, ABW, TWG, FCR and survival under the five treatment conditions (T_0 , T_2 , T_4 , T_8 and T_{12}) are presented in Table 1. It is interesting to note that no significant differences ($p > 0.05$) were found in any of these growth parameters. Selection of specimens of body weight in the range 21-23 g ensured that the stage of growth did not influence the growth character of the test specimens. At the end of the trials they attained body weight in a narrow range of 98.5– 103.7 g. Differences in the stocking density of the extractor plant (green bean) in the aquaponics system did not affect the survival and growth of the fish.

Growth performance of green bean

Growth performance data of green beans are presented in Table 2. The growth parameters selected to reflect this process are: average length of roots, average number of pods, average length of pods, average weight per pod

Table 1. Food conversion ratio and growth parameters of tilapia under different treatments. Values are means $\pm$ SE.

Parameters	Control (T0)	T2	T4	T8	T12
Specific growth rate ¹ , SGR	2.02 $\pm$ 0.08	2.00 $\pm$ 0.72	2.06 $\pm$ 0.05	2.05 $\pm$ 0.05	2.04 $\pm$ 0.03
Daily growth rate ¹ , DGR	1.24 $\pm$ 0.06	1.26 $\pm$ 0.04	1.30 $\pm$ 0.07	1.3 $\pm$ 0.02	1.29 $\pm$ 0.05
Survival rate ¹ , %	92.38 $\pm$ 1.9	93.33 $\pm$ 2.5	93.33 $\pm$ 2.5	98.10 $\pm$ 1.9	95.24 $\pm$ 0.95
Feed conversion ratio ¹ , FCR	1.04 $\pm$ 0.02	1.02 $\pm$ 0.01	1.07 $\pm$ 0.04	1.14 $\pm$ 0.01	1.13 $\pm$ 0.02
Average body weight gain ¹ , g	100.82 $\pm$ 1.9	98.50 $\pm$ 1.6	102.35 $\pm$ 1.0	103.78 $\pm$ 2.1	103.92 $\pm$ 0.9
Total weight gain ¹ , g	3547.58 $\pm$ 67.35	3515.32 $\pm$ 57.32	3759.23 $\pm$ 182.12	3954.35 $\pm$ 119.21	3756.01 $\pm$ 67.51

Table 2. Growth performance of green bean on different densities in the media-filled aquaponics system.

Parameters	T2	T4	T8	T12
Average length per pod (cm)	14.6 $\pm$ 0.4	14.2 $\pm$ 0.3	13.8 $\pm$ 0.6	14.7 $\pm$ 0.6
Average length of root (cm)	58.5 $\pm$ 3.0 ^b	56.3 $\pm$ 1.9 ^b	33.1 $\pm$ 1.8 ^a	31.0 $\pm$ 2.1 ^c
Average number of pods	52 $\pm$ 5.0 ^{ab}	67.3 $\pm$ 10.5 ^a	19.3 $\pm$ 3.2 ^b	18.3 $\pm$ 6.6 ^b
Average weight per pods (g)	6.8 $\pm$ 0.1	7.0 $\pm$ 0.1	6.7 $\pm$ 0.4	6.7 $\pm$ 0.5
Total biomass gain (g)	1083.6 $\pm$ 86.9 ^{ab}	1556.4 $\pm$ 88.9 ^a	404.6 $\pm$ 47.9 ^b	401.8 $\pm$ 98.1 ^b

and average biomass gain. It is evident from these figures that T4 treatment achieved the highest biomass gain as well as the number of pods while T12 treatment attained lowest of these values. The longest length of the root was seen in T2 treatment and shortest in T12 group. Significant differences ($p < 0.05$) were observed only in biomass gain, average length of root and average number of pods while there were no significant differences ($p > 0.05$) in the average length and weight of the pods. These observations are based on the plantlets of the green beans that started growing 7 days after the seed germination. This was the stage at which they were transferred to the aquaponics system.

In terms of appearance, the green beans looked healthy, with twisted vine, dark green leaves and normal branching. There were no signs of nutrient deficiency.

Water quality profile

Physico-chemical water quality parameters examined in the aquaponics system are shown in Table 3.

Water quality parameters did not vary significantly between the treatments except for pH. These were within the range for tilapia culture: Temperature (26.3–27.5 °C), dissolved oxygen (4.3–4.5 mg/L) and pH (<6). Because the experiment was performed under outdoor natural conditions, no special effort was needed to regulate physical conditions like temperature. In a tropical environment this is convenient, energy-saving and reduces the production cost.

The concentrations of NH₃-N, NO₂-N, NO₃-N and PO₄-P in each of the treatments are shown in Fig. 3. The data revealed that the fluctuations in NH₃-N occurred from the 1st to 13th week. The fluctuation trend was similar: decline in the concentrations that started from the first week continued over the second week (except for T2 and T12), followed by a steady increase until the seventh week, decline until the ninth week and subsequently increasing to thirteenth week (except in treatment T4).

The range of variation in the NO₃-N was highest (2–21 mg/L) across the treatments and the pattern was in the form of a decline on week 5, and notable increase in week 7 which continued until week 13. The NO₂-N the con-

Table 3. Temperature, dissolved oxygen and pH in each treatment (means $\pm$ SE): T0 (control, without plant), T2 (with 2 plants), T4 (with 4 plants), T8 (with 8 plants), T12 (with 12 plants).

Parameter	T0	T2	T4	T8	T12
Dissolved oxygen	4.40 $\pm$ 0.15	4.48 $\pm$ 0.12	4.53 $\pm$ 0.17	4.30 $\pm$ 0.14	4.39 $\pm$ 0.16
pH	5.91 $\pm$ 0.1 ^a	5.81 $\pm$ 0.08 ^a	6.34 $\pm$ 0.12 ^b	6.04 $\pm$ 0.1 ^a ^b	5.85 $\pm$ 0.05 ^a
Temperature, °C	26.83 $\pm$ 0.65	27.58 $\pm$ 0.35	27.46 $\pm$ 0.38	27.66 $\pm$ 0.31	27.51 $\pm$ 0.30

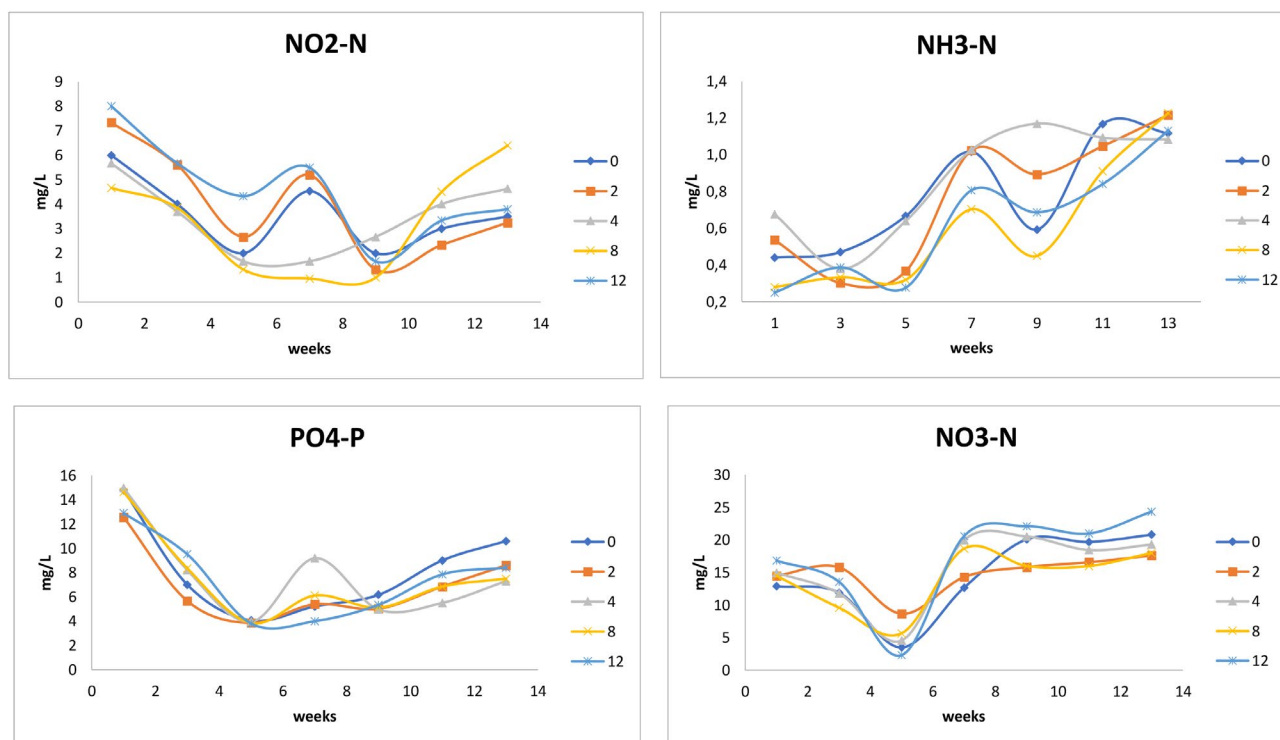


Figure 3. Concentrations of ammonia (NH₃-N), nitrite (NO₂-N), nitrate (NO₃-N) and phosphate (PO₄-P) in each of the treatments: T0 (without no plant), T2 (with 2 plants), T4 (with 4 plants), T8 (with 8 plants) and T12 (with 12 plants).

centration was slightly higher compared to that of NH₃-N in the first week of the culture period. Moreover, it can be seen from the Fig. 3 that the concentration of phosphorus was higher in the beginning, after that the fluctuation occurred from the end of week 1 with a decline in 5, followed by increase until week 7, decrease again to week 9, but increase from week 9 onward in all the treatments. Strikingly, the fluctuations in NH₃-N, NO₂-N, NO₃-N and PO₄-P generally followed a somewhat similar pattern in each of the treatments.

Discussion

GIFT growth performance

Growth of GIFT has been a subject of thorough investigations in the past. This fish has been cultured in ponds and tanks and other grow-out systems and observed for its survival and growth. Tilapia culture in aquaponics systems is a relatively new interest. There are several advantages of the aquaponics system. The foremost are conservation of natural resources, especially freshwater, environmental compatibility, product quality and logistical convenience. Production is more efficient in aquaponics compared to that in earthen ponds. This is evident when results obtained in this study were compared to those published by Bahnasawy *et al.* (2003). This can be attributed to a more efficient use of protein content in the feed

and its conversion into biomass. According to Kpundeh *et al.* (2014) this efficiency of protein conversion could be 25–30% higher.

The data on feeding and growth of the fish integrated with the green bean plant reflects the efficiency of nutrient assimilation in fish and cascading in the system. The low value of FCR (1.04–1.13) is a good indication of the high-quality feed that the fish can efficiently convert into tissues, and thus requires it in smaller quantity to produce a unit weight gain. Tacon & Metian (2008) established FCR of 1.0–2.4 for farmed fish and shrimp. This is important for a successful production because of the relationship between FCR and growth parameters such as SGR and daily weight gain at any water temperature, fish size and amount of digestible energy in the feed (Kolster, 1995). It can help in predicting growth of the fish and profitability of the aquaponics. Thus, in this study on GIFT the high value of SGR (2.02–2.04) can be interpreted in terms of efficient nutritional management as reflected by low FCR. These observations are comparable to the data published earlier. Wing-Keong *et al.* (2008) who worked on GIFT published data where FCR, average daily weight gain, FCR and SGR were 1.35–1.45, 0.67–0.76 g/day and 2.18–2.35 % / day, respectively. It is interesting to note that the variations in plant stocking density in the range selected for this study did not significantly influence the FCR and growth parameters of tilapia. This could be due to the ability of the green bean to modulate its nutrient uptake in the plant grow-bed area as long as the profiles of

key nutrients are within the limits that define the critical standing crop. In such a system the chemical homeostasis prevails without the water quality impairment in the fish-holding area. Mechanisms of optimization of water quality in production of co-cultured species of fish and plant is a topic of vital importance in sustainability, resilience and success of aquaponics (Rakocy *et al.*, 2014; Yildiz *et al.*, 2017; Maucieri *et al.*, 2019). Supply of the same type of feed (tilapia starter pellet with 34% protein) in all the treatments and the total volume of water and GIFT stocking density selected are the other factors that contributed to this stability. Earlier, Lam *et al.* (2015) also noticed that similarity in nutrient supply to the stocked fish accounted for preventing any significant fluctuations in the FCR value. Lack of differences in the growth performance of GIFT with the change in the rate of stocking of green bean also implies that the dynamic equilibrium in water quality parameters is within the tolerance limits of GIFT.

Green bean (*Phaseolus vulgaris*) growth performance

Analysis of the data on growth of green bean roots, number of pods and biomass gain reveals a positive growth when plant stocking density was 2 (T2) and 4 (T4) but the trend was reversed towards a decline when the stocking rate was 8 (T8) and 12 (T12). These differences were significant and seem to be linked to the quantity of nutrients in the system, with sufficient amounts in T2 and T4 while inadequate levels in T8 and T12. The comparable levels of metabolic waste (nutrients) in T2 and T4 that supported the plant growth indicated their optimum levels in the water (Lam *et al.*, 2015).

The growth of roots is important as it influences the nutrient uptake from the water to support biomass of green beans. Furthermore, the roots also provide space for the nitrifying bacteria that facilitate the conversion of NH_4^+ to nitrite NO_2^- and finally to nitrate, NO_3^- . The end product (NO_3^-) is absorbed by the plants for their growth (Estim *et al.*, 2018). Significance of the mechanism of bacterial nitrification has been highlighted by Endut *et al.* (2011). It is obvious from these observations that despite the root system helping in the nitrification process, roots of more plants will absorb greater amounts of nutrients as their surface area is also a key factor in the nutrient uptake. This can cause shortage of nutrients and impairment of the growth rate (Forbes & Watson, 1992). Another factor may be the capacity of the tank for the roots to function. Limitation of space can interfere with the efficiency with which nutrient uptake takes place in the roots. Where nutrient levels are in the suitable range as in T2 and T4 tanks, the size and weight of pods show no significant differences ($p>0.05$). From this observation

it appears that the optimum number of green beans for the area provided in the hydroponic tank (50 cm x 35 cm) is four. The important factor for yield of green beans is the number of plants per unit area and the pattern of spacing of the plants in the cultivation area (Forbes & Watson, 1992). Because the pattern of spacing of the plant was not manipulated or modulated in this study, it remains a topic of interest for further investigations. It is vital to have the precise plant density to achieve maximum production. Underutilized resources such as sunlight, photosynthesis and mineral nutrients generated in the system need to be made use of. The decreasing space between plants will cause interference in their growth. When the leaves are shaded and unable to get sufficient exposure to sunlight, the photosynthesis will be affected, and this will curtail the biomass gains.

Water quality profiles

The optimal range of water temperature for GIFT culture is 26–29 °C (Qiang *et al.*, 2018) and mortality rate increases above 37 °C. Data published by El-Sayed (2006) indicated that the growth rate of tilapia cultured at a temperature of 28 °C was comparable to growth at 24 °C and 32 °C. These investigations point out the need for maintaining optimum temperature in the aquaponics and suitability of the culture conditions in a biodynamic farming system of aquaponics.

The pH range of 5.81–6.34 in this system appears to be suitable for aquaponics. It is cost-saving as well as practical since the level is established by the processes taking place in the aquaponics and seeking to establish homeostasis. The photosynthesis and nitrification process occurring in the aquaponics system cause the fluctuation of pH (Ebeling *et al.*, 2006) but a dynamic equilibrium that prevails does not constrain the growth of the fish. Martins *et al.* (2018) have earlier noticed that pH within the range 6.5–7.5 allowed active growth rate and food conversion in tilapia.

El-Sayed (2006) published data on tolerance of tilapia in captivity to pH 4–11 and found survival to be 82.2% for fingerlings (0.41–1.0 g) and 100% for adults (45.4–46.3 g) at pH 4–5. Further reduction in pH to 3–2 resulted in heavy mortality. Ginneken *et al.* (2005) exposed tilapia strain *Oreochromis mosambicus* to pH 4 for 37 days and noticed that while mortality did not occur and the fish managed to maintain the ionic balance but the appetite declined. If the nutrient dynamics or other processes decrease the pH to the extent of causing stress to the fish, the solution proposed by Lekang (2013) is addition of appropriate quantities of calcium carbonate (CaCO_3) for its buffering capacity. While for pH, the result gained from this study was slightly lower compared to that in the study done by Haque *et al.* (2016) who

obtained better growth performance of GIFT when cultured at pH 7.08–7.88.

The concentration of DO in this farming unit was slightly below the suitable range (5.19–5.26 mg/L) for healthy survival and growth of GIFT as suggested by Haque *et al.* (2016). This is consistent with the recommendations of Boyd & Tucker (1998) who proposed that the warm-water fish grow faster and healthier when the DO concentration is > 5 mg/L. The authors further explained that when the concentration of DO is < 5 mg/L, fish attempts to compensate it by behavioral and physiological adjustments, including reduced physical activity and metabolic demand to compensate the increased ventilation rate. Because the DO level in the aquaponics was > 5 , no stress behavior or compensatory activities were seen in the fish. Increasing the DO concentration by way of aeration as done in this experiment is suggested to prevent the oxygen shortage and to support unhindered growth of the fish. Rate of aeration would depend on the stocking density. A reason for high tolerance of tilapia is its ability to make use of atmospheric air to overcome shortage of DO in water but this increases surfacing activity and hence the metabolic demand, resulting in loss of energy.

As for the water nutrient profiles, in treatments T2 and T8 the ammonia concentration was 1.0 mg/L and 1.2 mg/L, respectively. The maximum level for tilapia in culture systems for short periods is 1mg/L (Crab *et al.*, 2008), beyond which the captive stocks suffer stress and even mortality in a prolonged exposure at 1-2 mg/L. In treatments where the ammonia concentration increased from this limit, the causative factors could be inefficient bacterial bioremediation and unhealthy condition of the plants which happens towards the end of the experimental period. Renewal of water and replacement of plants as and when required can address this problem. As mentioned before, there are three distinct phases of growing green beans, namely start of the root formation, formation of stem and leaves (phase 1, 0-4 weeks), flowering that eventually results in the formation of pods (week 5 to 10) and the third phase when the plant has reached the harvesting stage (week 6 to 13). This plant begins to die after the week 14. These phases influence the nutrient profiles in water (Fig. 3). The highest concentrations of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ at the commencement of the experimental trial may be due to release of the fish specimens in the aquaponics system 2 weeks earlier for acclimatization and promoting the growth of nitrifying bacteria. Rise in $\text{PO}_4\text{-P}$ after week 7 in most of the treatments seemed to be linked to nutrient release by the GIFT into the water column and inefficient circulation of water at the tank bottom (Haque *et al.*, 2016). The intervening period before the starting and end phases was characterized by the rapid growth, and this coincided with significantly reduced amounts of nitrogen and phosphorus. This sort of pattern has also been mentioned for polyculture (Yuan

et al., 2010). The variations in nutrient dynamics in the present system are limited due to restricted size of the culture tanks (1.5 m²), rapid recycling of water from plant filter tanks to the fish tank and back due to the design of the facility where the plant filter tank is just next to fed fish tank, without long loops and with one water pathway based on gravity flow.

It is evident from the foregoing discussion that aquaponics is an area of aquatic farming that combines an efficient production of fish and vegetables in a recirculating aquaculture system that has a low carbon footprint. Eco-design is essential to reduce the environmental impact, and to increase the production efficiency and the economic profitability of the system. Technical specifications influence the water quality, water flow dynamics and health of the stocked organisms. The results of this study leave no doubt on the suitability of tilapia for aquaponics and significance of appropriate feed given to it for an efficient nutrient cascading that augurs well for healthy growth of the fish and availability of nutrients in the plant grow-bed. A proper stocking density of fed species (fish) and extractor (plant) together with the design of the system are critically important for the success of aquaponics. This experiment demonstrated that the production efficiency of green beans differed with their stocking densities. Interestingly, there was no significant influence on growth and yield of the GIFT. It also reflects that modulation of densities of the stocked species requires optimization not just in the number and biomass but also species depending on their levels of tolerance to the water quality dynamics in different sections of the aquaponics.

Being a new interest, aquaponics has received more attention towards critical water quality limits for fish while there are knowledge gaps as far as the integrated plant species are concerned. The most likely reason is the nature of biodynamics of nitrogen cycle in the aquaponics unit. Nitrogen that appears in the system from feed consumption is in the form of highly toxic ammonia that flows into the plant grow-bed where it is subjected to the process of nitrification that converts toxic ammonia into nitrite and nitrate which is taken up by the plant for building tissues and growth. Data on the factors that influence the nitrogen uptake can help in making informed decisions on biomass stocking rates where fish welfare and quality of plant production determine the and profitability. There is a vast scope for innovation in fish feed formulation that will further optimize nutrient uptake and water quality modulation, contributing to better homeostasis in this integrated hybrid culture system.

The potential benefits of aquaponics should be properly communicated to the target audience, especially the potential of this sector in innovative start-ups, supply of food to conscious consumers who care about locally grown fresh food and environmental compatibility of the

farming methods. Scaling up of aquaponics for commercialization will depend on the overall profitability of the system and consumer demand.

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