A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system

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A B S T R A C T

The growths of the African catfish (Clarias gariepinus) and water spinach (Ipomoea aquatica) were evaluated in recirculation aquaponic system (RAS). Fish production performance, plant growth and nutrient removal were measured and their dependence on hydraulic loading rate (HLR) was assessed. Fish production did not differ significantly between hydraulic loading rates. In contrast to the fish production, the water spinach yield was significantly higher in the lower hydraulic loading rate. Fish production, plant growth and percentage nutrient removal were highest at hydraulic loading rate of 1.28 m/day. The ratio of fish to plant production has been calculated to balance nutrient generation from fish with nutrient removal by plants and the optimum ratio was 15–42 gram of fish feed/m² of plant growing area. Each unit in RAS was evaluated in terms of oxygen demand. Using specified feeding regime, mass balance equations were applied to quantify the waste discharges from rearing tanks and treatment units. The waste discharged was found to be strongly dependent on hydraulic loading rate.

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1. Introduction

Aquaculture probably the fastest growing food-producing sector, now accounts for almost 50% of the world’s food fish and is perceived as having the greatest potential to meet the growing demand for aquatic food. It is estimated that at least an additional 40 million tonnes of aquatic food will be required by 2030 to maintain the current per capita consumption (FAO, 2006).

When fish are cultured, only a small proportion of the feed is converted (25–30%) to useable energy (Rakocy et al., 1993). The balance of nutrients is excreted in solid and dissolved fractions. Dissolved nutrients accumulate in recirculation systems with low water exchange and high feeding rates to levels which approximate hydroponic nutrient solutions.

Recirculation aquaponic system (RAS) is a promising technology in the integration of fish and hydroponic plant production. The fish water, rich in nutrients is used for plant growth, while the plants are used as biofilters for water regeneration. Whilst biofiltration converts the harmful into the harmless, the end point is a buildup of nutrients within recirculation systems, principally consisting of nitrates and phosphates. Nutrient removal by plants improves the quality of effluent and may enhance fish production. The amount of nitrate produced in a fish culture system is directly proportional to two factors: the amount or density of fish in the system and the amount and protein content of the food, as different fish species require different protein content in their respective diets.

Integrated systems use water more efficiently through the interacting activities of fish and plants. The addition of water to a fish tank to satisfy the oxygen requirements depends on the oxygen consumption of the fish, the oxygen concentration in the inlet water and the lowest acceptable concentration in the outlet water (Lekang, 2007). Hence effective HLR can be employed to achieve optimal growth for the fish and plants.

The rate of change in nutrient concentration can be influenced by varying the ratio of plants to fish (Rakocy et al., 2006). However, since the relative proportions of soluble nutrients made available to the hydroponic plants by fish excretion do not mirror the proportions of nutrients assimilated by normally growing plants, the rates of change in concentration for individual nutrients differ. The disparity in accumulation or reduction rates of different nutrients quickly results in suboptimal concentrations and ratios of nutrients, thereby reducing the nutritional adequacy of the solution for plants. Theoretically, the nutrient content of a diet can be manipulated to make the relative proportions of nutrients excreted by fish more similar to the relative proportions of nutrients assimilated by plants. With such a diet, there would be an optimal...
ration of fish to plants and optimal nutrient supplementation (Sea-
wright et al., 1998).

Several mass balance models have been proposed from previous
studies (Pagand et al., 2000; Papatryphon et al., 2005; Schneider
et al., 2005; Mongirdas and Kusta, 2006), from which the total
nitrogen and phosphorus discharges into receiving waters can be
estimated. However, most of these studies were conducted in open
systems. Recently, the incorporation of recirculated fish with veg-
etable hydroponics production has become an interesting model to
private sector, aquaculture and environmental scientists (Rakocy
et al., 2006; Bakhsh and Shariff, 2007; Endut et al., 2009).

The objectives of this study were to (1) determine the optimum
hydraulic loading rate in term of fish production, plant production,
and nutrient removal, (2) evaluate the optimum plants ratio in
term of daily fish feed input to plant growing area, and (3) study
the mass balance of oxygen in achieving sustainable balance be-
tween fish and plants.

2. Methods

2.1. Experimental design

The recirculation aquaponic system (RAS) utilized is depicted in
Fig. 1. The experimental facility was located in a greenhouse of the
University of Malaysia Terengganu campus. RAS consisted of a
fiberglass rearing tank, hydroponic trough (growing bed), sand fil-
ter for solid removal, sump system for denitrification unit, water
holding tank and reservoir (pre-aeration). Pipelines made of poly-
vinyl chloride were installed to connect the culture tank and
hydroponic trough to recirculate the water.

Three culture tanks arranged in series were used in the rearing
of African catfish (Clarias gariepinus). Air stones, connected to an air
blower were installed in the culture tank to supply oxygen for fish
culture. Water level in each culture tank was kept at 0.85 m deep
to maintain the water volume at 1000 L. Water lost through evap-
oration, transpiration and sludge removal was replenished with
water in the pre-aeration tank. The tank openings were covered
by plastic net (20 mm apertur) to hinder the fish jumping out of
the tanks. Measurements of temperature, dissolved oxygen (DO)
and pH of water samples were performed in situ during the sam-
ping process using the YSI multi-probe meter (model YSI 550A)
and pH Cyber Scan waterproof, respectively. Water temperature
and pH were in the range of 27.5–28.8 °C and 5.6–7.3 respectively
and was acceptable for African catfish.

Samples of C. gariepinus fingerlings, with an initial average body
weight of 30–40 g were randomly transferred into three replicate
fiberglass culture tanks. Water exited and flowed from the culture
tank was sprinkled over the vegetables in the hydroponic trough
and outflow trickled down to the sump for denitrification process.
The components were installed such that the water flowed by
gravity, by placing components at appropriate elevation relative
to one another. The water was then pumped vertically to the sand
filtration tanks for particulate removal. After exiting the sand filter
the water went directly to water storage tank and was flowed by
gravity back to the fish tank. During this study the inflow rates
of the RAS were maintained to be identical as possible by adjusting
the gate valves according to the target rate of each trial.

In the first experiment, five trials were consecutively performed
different hydraulic loading rates, each operating for 35 days and
compared with control with no plants. Each treatment was repli-
cated thrice. The experimental was operated with fish for one week
prior to the initiation in order to acclimate the biofilters as to min-
imize net nutrient uptake by bacteria at the beginning of each trial.

At the initiation of hydraulic loading rate of 0.64 m/day, system
was flushed and fingerlings African catfish were added to each cul-
ture tank up to the treatment biomass. Due to our inability to
obtain fish of similar size for trials two and three, fish from the
prior trial were pooled and reallocated to the systems for the fol-
lowing trial. Hand feeding, twice per day at the range of 2–4% body
weight/day. Fish were fed with 3.2 mm commercial diet floating
pellet (Cargill Company) with 32% protein and 10% moisture. The
food size was adjusted to compensate for changes in fish size.

Water spinach seedlings were planted directly into the gravel sub-
strate of the hydroponic growing bed at 10 cm × 10 cm spacing.

In the second experiment, the effect of seven ratios of plants to
fish (2, 4, 6, 7, 8, 9 and 10) was evaluated by manipulating water
spinach stocking rate. The size of the hydroponic trough and sys-

tem volume were the same for all ratios, but the daily feeding rate
increased in direct proportion to the fish biomass. African catfish
were stocked into rearing tank as at optimum HLR obtained in
the first experiment. Water samples from outlet of fish tank and
outlet of the hydroponic trough were collected once a week for
water quality determination. At the end of the experiment, all
fishes in each tank will be netted, weighed and their individual
lengths will be recorded as well as the weight of vegetable.

Fig. 1. A: Culture tank, B: hydroponic trough (planted bed), C: hydroponic trough (control bed), D: filter, E: sprinkler, F: sump, G: pump, H: rapid sand filter, I: water storage
If nutrient flows are subsequently connected from one system to another one, overall system nutrient retention and balances can be estimated. The oxygen flows and its retentions were calculated using mass balances, based on the concept: output = input – retention. This retention can be expressed as g per kg feed with the feed to the fish (percent fish nutrient). The nutrient discharges (output) from the system serve as input in the other subsequent system. Table 1 illustrates the hydraulic condition for this study.

2.2. Measurement of growth and yield

To assess the overall system performance, data on fish growth and feeding were collected. The feeding data collected include, the feeding rate, amount of feed; number of feeding/day; feed amount per tank per day; total feed per day and feed protein. Fish (10%) were taken from the culture tank to measure their length and body weight to estimate the growth rate of the fish and assumed to be representative of the fish in the tanks. The growth of fish was also monitored from the time at stocking up till the harvest time. Fish sampling in juvenile and grow-out systems were done on a weekly basis for survival and average weight.

The following production parameters were determined according to the procedure of Ridha and Cruz (2001):

\[ \text{Specific growth rate (SGR)} = \left( \frac{\ln \text{final weight (g)}}{\ln \text{initial weight (g)}} \right) \times 100 \text{ culture days} \]

\[ \text{Feed conversion ratio (FCR)} = \frac{\text{total weight of dry feed given}}{\text{total wet weight gain}} \]

Plants growth was monitored weekly by measuring the plant height of all water spinach plants on a 0.5 m² planting area accompanied by counting of number of shoots. The plants were harvested at height ranging from 45 to 50 cm. Each growing trough was cleaned and the biomass of plants was measured and recorded.

### Table 1

<table>
<thead>
<tr>
<th>Q (m³ day⁻¹)</th>
<th>HLRᵃ (m day⁻¹)</th>
<th>HRTᵇ for overall system (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>0.64</td>
<td>4.5</td>
</tr>
<tr>
<td>9.2</td>
<td>1.28</td>
<td>2.3</td>
</tr>
<tr>
<td>13.8</td>
<td>1.92</td>
<td>1.5</td>
</tr>
<tr>
<td>18.4</td>
<td>2.56</td>
<td>1.1</td>
</tr>
<tr>
<td>23.0</td>
<td>3.20</td>
<td>0.9</td>
</tr>
</tbody>
</table>

ᵃ HLR, hydraulic loading rate, which is flow rate (Q) divided by total surface area of the trough.
ᵇ HRT, hydraulic retention time which can be computed as (surface area x water depth x porosity of gravel trough/flow rate).

2.3. Samples analyses

Water samples were taken once a week from each culture tank, influent and effluent of the hydroponic trough, sump, water storage tank and inflow of culture tank. The samples were analyzed for 5-day biochemical oxygen demand (BOD₅), total suspended solid (TSS), total ammonium nitrogen (TAN), nitrite nitrogen (NO₂⁻–N), nitrate nitrogen (NO₃⁻–N) and total phosphorus (TP). Dissolved oxygen, pH, and temperature were also recorded each time water was collected. Weekly sampling was carried out between 8.30 am and 9.30 am in each sampling date and refrigerated at 4 °C in labeled polythene bottles for chemical analysis. The BOD₅ and TSS analyses were performed according to Standard Methods (APHA 1998). The TAN, NO₃⁻–N, NO₂⁻–N and TP measurements were performed using HACH DR4000 spectrophotometer according to salicylate, diazotization, cadmium reduction and ascorbic acid method respectively. The DO and pH of the sample were measured using DO meter YSI 55A and pH cyber scan waterproof respectively.

2.4. Statistical methods

Statistical software of Statistical Package for the Social Sciences (SPSS) Version 16 and Microsoft Excel were used to calculate mean, standard deviation, and one-way ANOVA. Differences of mean were evaluated for significance by the range tests of Tukey HSD (p ≤ 0.05) for homogeneous variances (Levene test) and by the range test of Dunnett T3 (p ≤ 0.05) for inhomogeneous variances, respectively (Schulz et al., 2003).

3. Results and discussion

3.1. Effect of hydraulic loading rates

Specific growth rates (SGRs), feed conversion ratio (FCR) and fish production did not differ significantly between hydraulic loading rates (Table 2). FCR values are in the range of 1.23–1.39. In our study, the same feed is used and the ration is fixed similarly in all culture tanks. Stocking at hydraulic loading rate of 1.28 m/day gives the best production performance (Table 2).

The FCR recorded (1.23–1.39) is not far above the ideal value of 1.0 for culture of African catfish in recirculation system and FCR value 0.85 reported in the culture of African catfish by Eding and Kamstra (2001). However the recorded FCR are better than the range 1.1–1.7 reported in recirculation system of African catfish as reported by Akinwole and Faturoti (2007). HLR did not affect growth rate or feed conversion ratio.

Plants grew actively in the hydroponic trough and did not identify any nutritional deficiencies or mineral imbalances. Plant
production increased as the hydraulic loading rate increased from 0.64 m/day to 1.28 m/day, whereas an increase in the HLR from 1.28 m/day to 3.20 m/day did not result in a higher plant production. At the end of the growth period (20–28 days), the plants reached the market size at average height of 45–50 cm. Whole plant water spinach growth rate and yields differ significantly between hydraulic loading rates (Table 2).

Plant growth rate and productions differ significantly between HLR. The growth decreased significantly with increasing in HLR supported the development of aerobic conditions in the hydroponic trough and hindered denitrification processes. Nevertheless, low HLR with lower out flowing oxygen contents promoted denitrification and highest NO\textsubscript{3}–N accumulation of NO\textsubscript{3}–N is nitrified, subsequent denitrification is limited. Possible factors that could limit denitrification include inadequate residence/retention time for the sump to denitrify NO\textsubscript{3}–N, the presence of DO, or lack of available carbon in the system.

A number of mechanisms are responsible for the removal of NO\textsubscript{3}–N from the wastewater. One mechanism for the removal of NO\textsubscript{3}–N is plant uptake through the root system from the growth quantity. The major growth-limiting mineral is usually nitrogen and highest growth rates and yields are generally seen when nitrogen is supplied as combination of ammonium and nitrate.

Continuous flow operation of the aquaponic system was initiated with a low HLR of 0.64 m/day. The mean value and percentage removal of water quality variables at various HLR are shown in Table 3. It is found that removal percentage of BOD\textsubscript{5}, TSS, TAN and Nitrite–N increased with increasing in HLR. In contrast to BOD\textsubscript{5}, TSS, nitrite–N and TAN, removal percentage of nitrate–N and TP increased with increasing in HLR from 0.64 m/day to 1.28 m/day and decreased with increasing in HLR from 1.28 m/day to 3.2 m/day. Statistically, there were significant differences in all water quality parameters by HLR (p < 0.05) as shown in Table 3. The whole treatment, RAS basically showed effective nutrient removal with average reduction efficiency range from 47% to 89.5%.

Values of TSS, BOD\textsubscript{5}, TAN, nitrite–N, nitrate–N and total phosphorus in final effluent from this study are in accordance with the previous studies (Eding and Kamstra, 2001; Schulz et al., 2003; Franco-Nava et al., 2004; Lin et al., 2005; Snow and Ghaly, 2008). The optimum hydraulic loading rate can be determined by a compromise between fish and plant productions and removal efficiency.

Similar to previous studies (Cottingham et al., 1999; Jamieson et al., 2003), the improvement in TAN removal is paralleled by the increase in NO\textsubscript{3}–N. It can be concluded that the improvement in ammonia removal is due to increased nitrification activity. The accumulation of NO\textsubscript{3}–N in the system indicates that after NH\textsubscript{3}–N is nitrified, subsequent denitrification is limited. Possible factors that could limit denitrification include inadequate residence/retention time for the sump to denitrify NO\textsubscript{3}–N, the presence of DO, or lack of available carbon in the system.

A number of mechanisms are responsible for the removal of NO\textsubscript{3}–N from the wastewater. One mechanism for the removal of NO\textsubscript{3}–N is plant uptake through the root system from the growth medium. A second mechanism for the removal of dissolved solids is microbial assimilation. It may also be assimilated by microorganisms in the water column or by biofilms associated with the root mats of plants (Vaillant et al., 2004).

Denitrification activity is reduced if available carbon supplies were low and proceeds only when the oxygen supply was inadequate for microbial demand (Hamlin et al., 2008). In this study, carbon availability may have been inadequate to support high levels of denitrification due to the lack of an established litter layer in the system. If, on the other hand, the influent wastewater itself is an adequate source of carbon, the lack of denitrification may be attributed to the short hydraulic retention time of the system.

### 3.2. Plant ratios

The percentage removal values of TAN, nitrite–N, nitrate–N, total phosphorus and plant productions at seven ratios of plants to fish are shown in Table 4. There was significant difference in TAN, nitrite–N, nitrate–N and total phosphorus concentrations between ratio of plants to fish. The percentage removal of water quality parameters and plant productions increased with increasing in plant ratios to fish until the maximum was reached at plant to fish ratio of 8, which was equivalent to a fish feeding rate of 15–42 g/m\textsuperscript{2} plant growing area. Further increasing plant ratios led to considerable decreases in water spinach production. This strongly concludes that insufficient nitrogen in the influent of hydroponic trough could be a limiting factor for a further increase in plant production.
In the field experiment conducted by Rakocy et al. (2006), a ratio in the range of 60–100 g of fish feed/m² of plant growing area was used for the production of tilapia, lettuce, basil and several other plants in raft aquaponic system. From our results we conclude that the technical demand on management, especially the fish and plant species used plays a vital role in the establishment of the configuration and relative size of integrated system components. Plant roots, hydroponic structures and media improve water quality by capturing solids and providing surface area for biofiltration.

### 3.3. Removal rate constant

Pollutant removal can be described using first-order kinetic model (IWA, 2000). Average first-order removal rate constants for a specific pollutant are determined by substituting mean hydraulic retention time (Table 1) and mean influent–effluent concentrations of the pollutant (Table 3) into the following equation, and then solving for $k$.

$$\frac{Ce}{Ci} = \exp(-kt) = \exp \left( \frac{kch_w}{HLR} \right)$$

(1)

where $Ce$, effluent pollutant concentration (mg/L); $Ci$, influent pollutant concentration (mg/L); $k$, first-order removal rate constant (day$^{-1}$); $t$, hydraulic retention time (day); HLR, hydraulic loading rate (m/day); $h_w$, porosity of hydroponic trough (assuming 0.45–0.70); and $w$, water depth of trough (m).

These results are shown in Table 5. Distinct values of removal rate constants for major pollutants have been reported and were evaluated using the same methods as this study with the influent–effluent data. The effect of hydraulic loading rate on removal rate constant was further examined by linear regression with logarithmic scale using the $k$-HLR data in Table 5. Good correlations with power function were found between removal rate constant and HLR for TAN as depicted in Fig. 2.

Removal rate constants for TSS, TAN, NO$_2$–N and NO$_3$–N, obtained from this study and other comparative studies (Schulz et al., 2003; Lin et al., 2005), are found to be proportional to hydraulic loading rate to a power equation. These suggest that removal rate constant would be varied depending on hydraulic loading rate. Efficient removal was always achieved in these studies under a wide range of hydraulic loading rate because of low pollutant levels of aquaculture wastewater, thus leading to HLR controlling the removal rate constant.

### 3.4. Oxygen concentration dynamics in RAS components

Figs. 3–5 show oxygen concentration dynamics in culture tank, influent planted trough and effluent planted trough, respectively. At the beginning of the system operation, the oxygen difference across the system components was insignificant because of the low system loading (low fish biomass and therefore low feed loading). At the end of the experiment, oxygen concentration in culture tank, influent planted trough and effluent planted trough then reached a value of 4.70 mg/L, 4.35 and 4.2 mg/L, respectively. The decreased of oxygen concentration with increasing in culture day due to the increase of fish biomass and accumulation of organic matter in the system.

### 3.5. Oxygen consumption in fish tank

Reared fish are the main oxygen users here. Oxygen demand depends on metabolic rate so the oxygen usage is expressed in terms

### Table 4

Percentage removal of water quality parameters and plant productions in RAS with hydroponic water spinach at seven ratios of plants to fish.

<table>
<thead>
<tr>
<th>Fish to plants ratio (1:x)</th>
<th>Percentage removal (%)</th>
<th>Water spinach production (g WW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TAN</td>
<td>NO$_2$–N</td>
</tr>
<tr>
<td>2</td>
<td>67.26$^1$</td>
<td>69.00$^1$</td>
</tr>
<tr>
<td>4</td>
<td>69.93$^2$</td>
<td>76.60$^2$</td>
</tr>
<tr>
<td>6</td>
<td>72.96$^3$</td>
<td>82.74$^3$</td>
</tr>
<tr>
<td>7</td>
<td>79.32$^4$</td>
<td>90.57$^4$</td>
</tr>
<tr>
<td>8</td>
<td>81.67$^5$</td>
<td>95.75$^5$</td>
</tr>
<tr>
<td>9</td>
<td>85.86$^6$</td>
<td>96.53$^6$</td>
</tr>
<tr>
<td>10</td>
<td>86.22$^7$</td>
<td>96.84$^7$</td>
</tr>
</tbody>
</table>

WW, wet weight.

Values given are mean from triplicate data ($n$ = 3); treatment with the different superscript within the same column is significantly different at the $p < 0.05$ level.

### Table 5

First-order removal rate constants at various HLR.

<table>
<thead>
<tr>
<th>HLR (m/day)</th>
<th>Removal rate constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_{TAN}$ (day$^{-1}$)</td>
</tr>
<tr>
<td>0.64</td>
<td>4.45</td>
</tr>
<tr>
<td>1.28</td>
<td>7.63</td>
</tr>
<tr>
<td>1.92</td>
<td>11.54</td>
</tr>
<tr>
<td>2.56</td>
<td>11.99</td>
</tr>
<tr>
<td>3.2</td>
<td>12.12</td>
</tr>
</tbody>
</table>
of feeding rate. Literature data (Bovendeur, 1989; Timmons and Losordo, 1994) report broad limits ranging from 200 g/kg to 610 g/kg of fodder used. Henceforth the value \( \frac{k_{o,p}}{\rho} = 368 \text{ g O}_2/\text{kg fodder/day} \) (Bovendeur, 1989) applied for African catfish rearing in RAS. One more portion of oxygen is required to oxidize the excess fodder and fish excretions. Thus, according to Mongirdas and Kusta (2006), the overall oxygen mass balance can be expressed as follows:

\[
24(Q + Q_p)\Delta C = (k_{o,p} \rho W m + R_{\text{BODT}} + R_{\text{NT}})(1 - WE),
\]

where \( Q \), recycled water (m³/day); \( Q_p \), supplemental water (m³/day); \( \Delta C \), oxygen concentration differential (g/m³); \( k_{o,p} \), oxygen used (g/kg fodder/day); \( W \), daily feeding rate, percent from body mass; \( m \), mass of reared fish (kg); \( R_{\text{BODT}} \), oxygen demand by heterotrophic organisms (g/m³/day); \( R_{\text{NT}} \), oxygen demand of the autotrophic (nitrifying) microorganisms for ammonia oxidizing (g/m³/day); \( WE \), water exchange in the system, and 24 is the dimension uniformly constant (day/hour). Oxygen usage dynamics is shown in Fig. 6.

The measured mean daily usage of oxygen in the units is expressed as \( M_{O_2} = 24Q\Delta C \) (kg/day); \( M_{O_2} \) is the calculated oxygen demand in the rearing units according to expression (2). The fish growing curve (Fig. 6) indicates the amount of the fodder fed and, therefore, the oxygen used. Water flow should be increased with the growth of fish. However, in this experiment water flow is kept the same from beginning to the end.

4. Conclusion

This study demonstrated that the changes in concentrations of different nutrients in aquaponic system differ because of the disparity between the relative proportions of available nutrients generated by fish and nutrients uptake by plants. The optimal HLR in term of fish productions, plant growth and percentage nutrient removal were found to be 1.28 m/day. Reviewing the calculated balances and limitations of intensive integrated aquaculture systems, the perspectives of such integration are very promising, as these systems require fewer nutrients in relation to overall production, and reduce nutrient discharge by reutilization. Development of the optimum conditions, e.g., HLR, plants to fish ratio, oxygen levels and water temperature, for system design and operation in RAS is vital in order to maximize fish and plant productions and nutrient recovery and minimize water exchange and nutrient accumulation as well as beneficial environmental impacts.

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