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# Use of planted biofilters in integrated recirculating aquaculture-hydroponics systems in the Mekong Delta, Vietnam

**Ngo Thuy Diem Trang**[1] **& Hans Brix**[2]

[1]College of Environment and Natural Resources, Department of Environmental Science, Can Tho University, Campus 2, 3/2 Street, Ninh Kieu District, Can Tho City, Vietnam

[2]Department of Bioscience, Aarhus University, Ole Worms Allé 1, Building 1135, 8000, Aarhus C, Denmark

**Correspondence:** N T D Trang, College of Environment and Natural Resources, Department of Environmental Science, Can Tho University, Campus 2, 3/2 Street, Ninh Kieu District, Can Tho City, Vietnam. E-mail: ntdtrang@ctu.edu.vn

## Abstract

The feasibility of using planted biofilters for purification of recirculated aquaculture water in the Mekong Delta of Vietnam was assessed. The plant trenches were able to clean tilapia aquaculture water and to maintain good water quality in the fish tanks without renewal of the water. $NH_4$-N was removed efficiently in the plant trenches, particularly in the trenches with *Canna glauca* L., probably because of plant uptake and nitrification–denitrification. Plant uptake constituted 6% of N and 7% of P in the input feed. Approximately 1.0 $m^3$ of water was needed per kg of fish produced, and 370, 97 and 2842 g fresh aboveground biomass of *Ipomoea aquatica* Forssk., *Lactuca sativa* L. and *C. glauca*, respectively, were produced. The leafy vegetables provide some extra income besides fish products, whereas *C. glauca* provides nice flowers and contributes to a significant nutrient removal with annual uptake rates of 725 kg N and 234 kg P $ha^{-1}$ $year^{-1}$. This research demonstrates that integrated recirculating aquaculture-hydroponics (aquaponics) systems provide significant water savings and nutrient recycling as compared with traditional fish ponds.

**Keywords:** Aquaponics, *Canna glauca*, *Ipomoea aquatica*, *Lactuca sativa*, nitrogen, tilapia

## Introduction

The Mekong Delta is by far the most productive area for aquaculture in Vietnam with a total production of 2.2 million tons in 2007 (General statistic office (GSO) 2009). Aquaculture practice in the Mekong Delta is dominated by extensive or semi-intensive production in earthen ponds, but in response to the increased domestic market and the national requirements for export, the aquaculture industry is presently increasing at an alarming rate, with consequent environmental problems and impacts. Aquaculture is most commonly practiced in ponds with frequent water exchange and renewal to ensure an adequate supply of oxygen for the fish as well as discharge of the waste products from the fish. This practice relies on a plentiful supply of good quality freshwater from adjacent rivers, but the discharge of untreated water from the aquaculture ponds to the same rivers deteriorates the water quality and acts as a vector for spreading of disease between different aquaculture systems (Thien, Dalsgaard, Thanh, Olsen & Murrell 2007; Nhan, Verdegem, Milstein & Verreth 2008). Hence, there is an urgent need to develop a more sustainable aquaculture industry that uses less freshwater and one that does not deteriorate the water quality of the rivers. Recirculating aquaculture systems are recognized as appropriate systems with minimal effluent discharge, efficient water reuse and optimal water conservation compared with conventional intensive fish ponds (Losordo, Hobbs & Delong 2000; Shnel, Barak, Ezer, Dafni & Rijn 2002; Rakocy, Masser & Losordo 2006; d'Orbcastel, Blancheton & Belaud 2009). However, to avoid accumulation of toxic concentrations of ammonia and nitrite in the water, it is necessary to integrate water treatment systems into recirculating aquaculture systems, such as various physical and biological filter systems (Ridha & Cruz 2001; Shnel *et al.* 2002; Davidson & Summerfelt 2005; El-Shafai, El-Gohary, Nasr, Steen & Gijzen 2007b). The excess nutrients and organic matter produced in the recirculating aquaculture system can also be processed in natural' ecosystems such as constructed wetlands (Lin, Jing & Lee 2003; Konnerup, Trang & Brix 2011), but these have relatively large footprints and do not grant any income for the farmer.

The integration of vegetables and other crop plants in the treatment system has been proposed with the aim of producing a second marketable crop from the nutrient rich fish water (Naegel 1977; Watten & Busch 1984; Lennard & Leonard 2006; Rakocy *et al.* 2006; Graber & Junge 2009). Most research and development of these systems has occurred in industrialized countries, but the potential application of such systems is far greater in tropical and subtropical regions because of the more favourable climatic conditions (van Rijn 1996). Earlier studies have shown that the two green vegetables, water spinach (*Ipomoea aquatica* Forssk.) and lettuce (*Lactuca sativa* L.), can be successfully grown in hydroponics culture under conditions similar to those in integrated aquaculture-hydroponics recirculating systems (Sikawa & Yakupitiyage 2010; Trang, Schierup & Brix 2010). In addition, information of integrating of ornamental plant, such as *Canna glauca* L., in the aquaculture-hydroponics system is limited in the Mekong delta, Vietnam. This study was conducted to assess the potential of using planted biofilters to purify water and to reduce the need for water renewal in aquaculture. The growth, biomass production and nutrient uptake of *I. aquatica*, *L. sativa* and *C. glauca* in a recirculating aquaculture-hydroponics system with tilapia were evaluated. The water quality and the fish production were monitored. Nutrient mass balance in the system was estimated based on inputs of feed pellets, nutrients incorporated into fish and plants, and nutrient accumulation in water and sludge.

## Materials and methods

### System setup

Three outdoor pilot scale integrated recirculating aquaculture-hydroponics (aquaponics) systems were constructed in triplicate at Can Tho University, Vietnam (10°01′ N, 105°45′ E). Each system consisted of a 1.47 m diameter composite fish tank (depth 0.85 m) and three composite plant trenches (length 2 m; width 0.7 m; depth 0.35 m) through which the water from the fish tank was recirculated. Water from the fish tank (volume 1 $m^3$) was distributed through Ø21 mm PVC pipes to the plant trenches by timer-controlled submersible pumps. The timers were set to run for 20 min every 2 h. The inflow at each plant trench was controlled by valves at 0.45 L $min^{-1}$ (total flow rate through each trench was 0.1 $m^3$ $day^{-1}$). The outflow from the trenches was collected in a plastic container (diameter 0.68 m; height 0.47 m) and was pumped back to the fish tank through a Ø21 mm PVC pipe and a sprinkler over the fish tank for aeration (Fig. 1).

### Fish and plant growth

Similar-sized (~71 g fresh mass) and disease-free tilapia fingerlings (*Oreochromis niloticus* L.) were selected and stocked at a density of 67 fish $m^{-3}$ (Soto-Zarazúa, Herrera-Ruiz, Rico-García, Toledano-Ayala, Peniche-Vera, Ocampo-Velázquez & Guevara-González 2010). During the experiment, the fish were fed twice a day with a commercial pellet (feed composition: 25% crude protein, 4% crude fat, 10% crude ash, 8% crude fibre, 4% nitrogen, 1.1% phosphorus and 11% moisture; Aquafeed GB625, Vietnam). The feed was distributed manually at a rate of 3% of estimated body weight of the fish per day, and the feeding rate was adjusted according to the growth of the fish. The fish growth-performance parameters were evaluated according to Azaza, Kammoun, Abdelmouleh and Kraïem (2009). After 25 days, when the microbial community in the trenches was expected to have stabilized, and again at the end of the study, the fish biomass was determined by weighing all fish. The feed conversion ratio (FCR) was calculated as the total feed dry mass divided by the increase in fish mass during the experiment.

Plant trenches were planted with 14-day old seedlings of *Ipomoea aquatica* and *Lactuca sativa* placed in individual plastic pots (height 100 mm; filled with 50 mm Ø10–20 mm gravel, and 50 mm of coconut fibre on top) at a density of 35 plants per trench. *Canna glauca* were planted directly in gravel at a density of 15 plants per

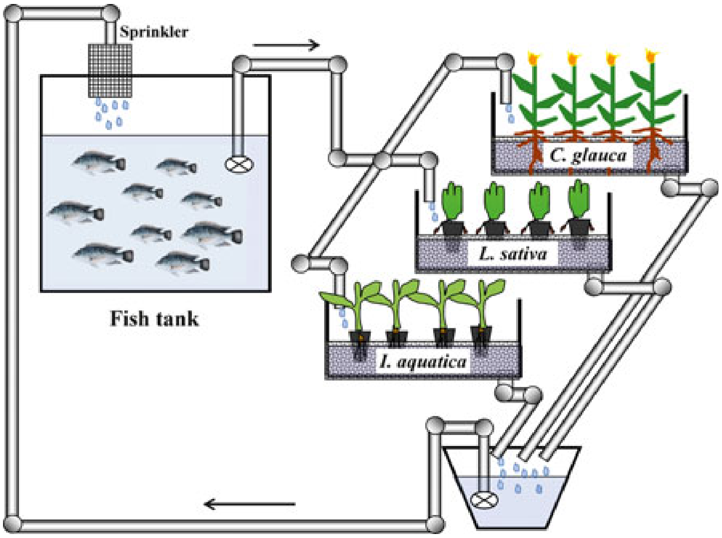

**Figure 1** Schematic presentation of the pilot scale integrated recirculating aqua-hydroculture system. Arrows indicate the direction of water flow. Dimensions not to scale.

trench. The water level in the trenches was controlled 20 mm below the surface of the gravel. Water quality monitoring was carried out during the following 25-day period until plant harvest. The 25-day period was chosen based on marketable size of *I. aquatica* after transplanting in the hydroponic trenches. At harvest, 10 plants from each trench were collected randomly and rinsed in water. Thereafter plants were fractionated into leaves, stems and roots to determine fresh and dry mass after drying at 70°C for 3 days. The remaining plants in the trenches were pooled and their fresh biomass was measured. The dried plant fractions were ground and the concentrations of N and P analysed using a NA 2000 N-protein analyzer (Fisons Instruments, Italy) and plasma emission spectrometry (ICP-AES, Plasma 2000, Perkin Elmer Instruments, USA).

## Water sampling and analysis

Water in the fish tanks was not exchanged during the experiment, but tap water was added (~0.02 $m^3$ $day^{-1}$) to replace water lost by evapotranspiration. Temperature, dissolved oxygen (DO), pH and electric conductivity (EC) of the water in the fish tanks and the effluent from the plant trenches were measured daily at 08:00–09:00 using portable meters. Water samples were collected and transferred immediately to the laboratory for water quality analysis (APHA 1998). Ammonium–nitrogen ($NH_4$-N) and orthophosphate ($PO_4$-P) were analysed in filtered samples using the salicylate method (a modified version of a photometric method by Lachat, Quikchem No. 10-107-06-3-A or B) and the ascorbic acid method respectively. Total phosphorus (TP) was analysed by the ascorbic acid method after acid hydrolysis in an autoclave for 30 min. Total Kjeldahl Nitrogen (TKN) was analysed using a Kjeldahl block digestion unit (Kjeldatherm KB 20S, Gerhardt, Germany) and distillation by a semi-automatic steam distillation unit (Vapodest 20, Gerhardt, Germany). Chemical Oxygen Demand (COD) was analysed using a COD reactor (HACH Instruments, Loveland, CO, USA).

## Sludge collection

The sludge accumulating in the fish tanks was collected at day 15 and 25. The sludge was withdrawn through a Ø34 mm PVC pipe at the bottom of the fish tanks, and then settled for 1 h in a volumetric cylinder. The settled sludge was dried at 105°C, weighed and the concentrations of N and P were analysed using procedures as described above.

## Nutrient mass balance

The N and P mass balances of the aquaponics systems were estimated based on the inputs into the system from feed, the uptake into the fish and plants, the amount removed in sludge and the accumulation in the water. The concentration of N and P in the fish meat was based on the findings of Tian, Li, Dong, Yan, Qi, Liu and Lu (2001), who reported proximate analyses of harvested Tilapia with a dry matter content of 24.5% and N and P concentrations of 9.8 and 4.31% dry mass respectively. The amount of N and P taken up by the plants was estimated based on the concentrations in the tissues and the biomass produced. The amount of N and P accumulated in the water during the experiment was based on the increase in concentration during the course of the experiment. The input from the added tap water was neglected.

### Statistical analysis

Data were tested for normal distribution and variance homogeneity (Levene's test) and logarithmically transformed if necessary. Differences in plant growth, nutrient uptake and plant biomass production between species were identified by one-way ANOVA. Differences in water quality of inlets and outlets were identified using two-way ANOVA (species × sampling times) using Type III sum of squares. Tukey Honestly Significant Differences (HSD) were used to identify significant differences between species at the 5% probability level. The software Statgraphics Centurion XV (StatPoint, Inc., USA) was used for all statistical analyses.

## Results

### Fish growth

The average amount of dry pellet feeding to the fish was 142 g per tank day$^{-1}$. There was no mortality of the fish throughout the experiment. The average specific growth rate of the fish was 1.56 (% weight day$^{-1}$). The fish fresh mass gain was 106 ± 33 g per tank day$^{-1}$ (mean ± 1 SD), which resulted in a mean feed conversion ratio of 1.4 ± 0.4 (mean ± 1 SD).

### Plant biomass and nutrient uptake

*Canna glauca* produced the highest amount of dry biomass at harvest and a significantly higher biomass than the vegetable species. *Ipomoea aquatica* produced four times more biomass than *L. sativa* (Fig. 2b). As a consequence of the high biomass production, *C. glauca* also took up the largest amount of N and P, followed by *I. aquatica* and *L. sativa* ($P < 0.01$) (Figs 2c and 2d). The estimated yearly productivity of *C. glauca* (based on Fig. 2a) was 2446 and 1355 g dry mass m$^{-2}$ year$^{-1}$ for above and belowground parts, respectively, whereas that of *I. aquatica* was much lower, namely 489 and 240 g dry mass m$^{-2}$ year$^{-1}$ for above and belowground fractions, respectively, and even lower for *L. sativa* (46 and 49 g dry mass m$^{-2}$ year$^{-1}$ for above and belowground fractions respectively).

### Water quality

The pH values in the fish tanks increased from pH~6.7 initially to pH~7.3 at the end of the experiment ($P < 0.05$), and fluctuated in the range of pH 6.4–7.6 (Fig. 3a). Dissolved oxygen (DO) concentration decreased over time ($P < 0.05$) and reached a very low level (<1.5 mg L$^{-1}$) at the end of the experiment (Fig. 3b). Electric Conductivity increased steadily throughout the experiment ($P < 0.05$) and ranged from 168 to 392 µS cm$^{-1}$ (Fig. 3c), and the water temperature increased over time and reached >31°C at the end of the experiment (Fig. 3d).

The quality of water entering the plant trenches (i.e. inlet) deviated somewhat in terms of pH, EC, DO and temperature from the quality in the fish tanks because of the residence time in the distribution pipes. Mean inlet and outlet quality of the three plant trenches over time are presented in Figs 3 and 4. Outlet pH was slightly lower than that in the inlets, particularly for the *C. glauca* planted trenches (Fig. 3a). Dissolved oxygen concentrations were always lower in outlets (<2 mg L$^{-1}$) than in the inlets (Fig. 3b). Outlet EC in the plant trenches increased over time in concert with the increase in EC in the fish tank, but the EC in the outlets of the *C. glauca* trenches were slightly lower than in the inlets, and more so at the end of the experiment (Fig. 3c). COD concentrations decreased during passage through the trenches (Fig. 4a). Total Kjeldahl Nitrogen and $NH_4$-N inlet concentrations were relatively low and constant throughout the experiment (Figs 4b and 4c), and concentrations in the outlets were significantly lower than in the inlets, and lowest in the outlets of the *C. glauca* trenches. Unfortunately, because of technical problems in the laboratory, we could not analyse $NO_2$–N and $NO_3$–N concentrations in the water. However, subsequent

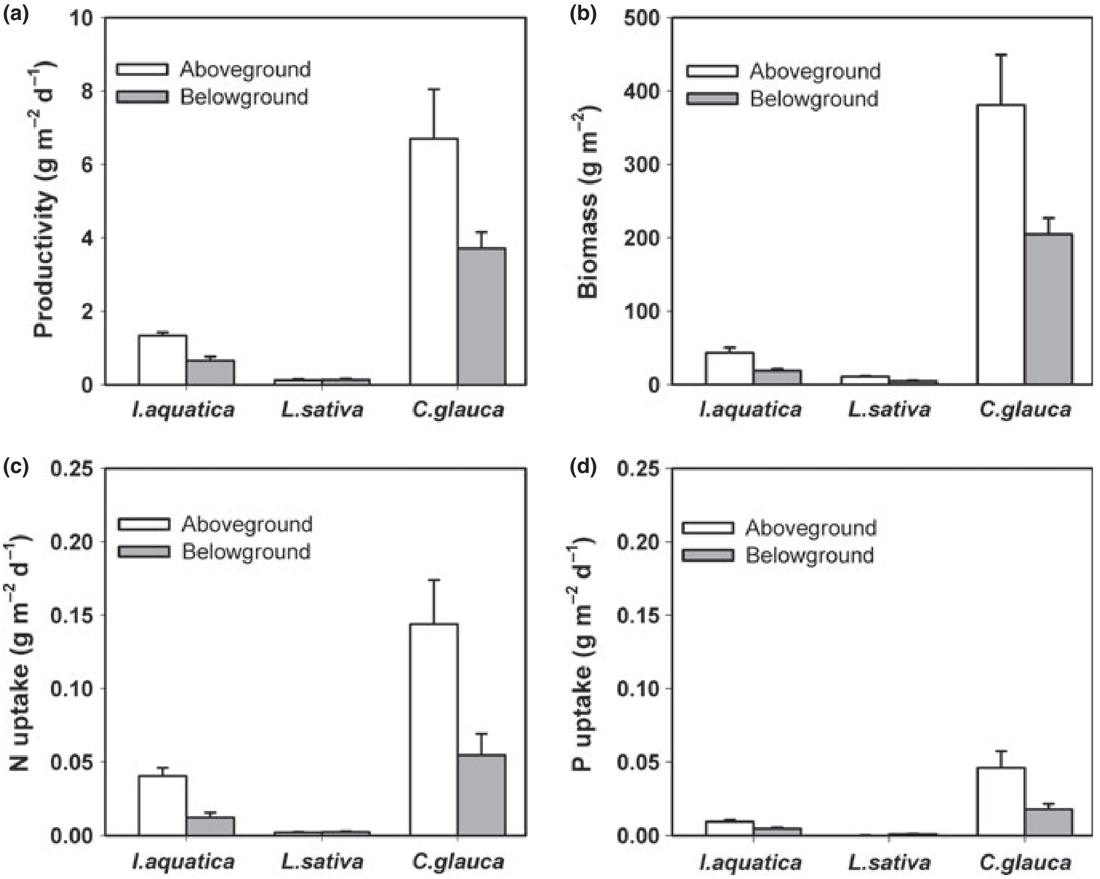

**Figure 2** Mean (a) productivity (DW), (b) biomass at harvest (DW), (c) nitrogen, and (d) phosphorus uptake rate of above and belowground fractions of *I. aquatica*, *L. sativa* and *C. glauca* during 25 days. Error bars are 1 SD ($n = 3$).

studies in similar set-ups showed that $NO_3$ did not accumulate in the systems ($NO_3$–N < 5 mg $L^{-1}$ and $NO_2$–N always <1 mg $L^{-1}$). For mass balance calculation we therefore used the TKN values, and neglected $NO_2$ and $NO_3$. Total Phosphorus and $PO_4$-P inlet concentrations had the same trend as TKN and $NH_4$-N, which were constant throughout the experiment. Outlet concentrations were generally slightly lower in the *C. glauca* trenches (Figs 4d and 4e).

### Nutrient mass balance

The system mass balance for N and P is presented in Table 1. The input to the mass balance is the amount of N and P in the fish feeding pellets. Outputs are the amount incorporated into the fish meat, the amount recovered in harvested plants biomass and the amount in sludge removed from the systems. The contents in fish and plants at the beginning of the period were subtracted from the amount at harvest. In addition, some N and P accumulated in the water during the experiment. On average, 45% N and 76% P from the input feed were incorporated into the fish meat, and the remainder was released into the water as uneaten feed, fish faeces and fish excretions. Only 2% N and 3% P from the input feed were removed from the system with the sludge collected, and 2% N and 5% P accumulated in the water. Also a relatively small fraction (6% N and 7% P from the input feed) was taken up and recovered in the plant biomass. Nearly half (45%) of the N, and 9% of the P added to the system with the feeding were unaccounted for in the mass balance.

## Discussion

For optimum fish growth in recirculating aquaculture systems, the water quality must be maintained within specific limits with adequate

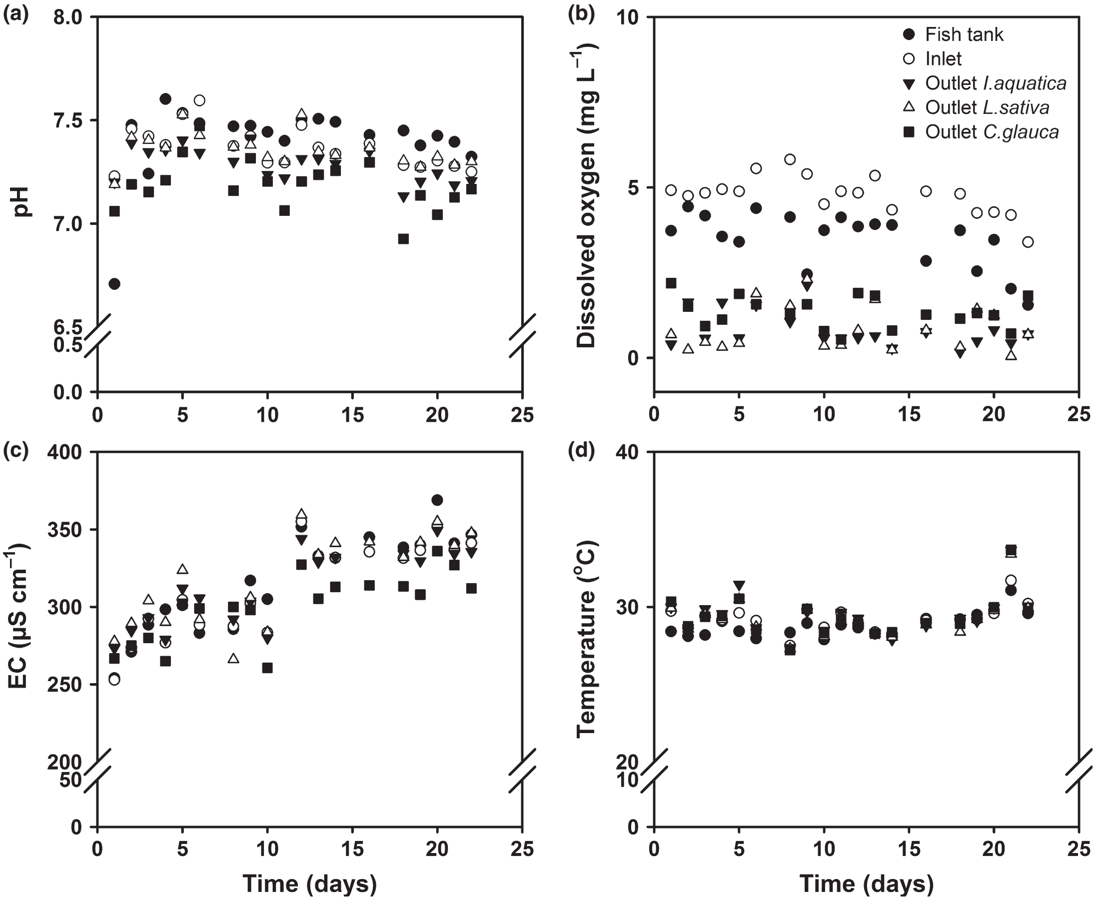

**Figure 3** Mean (a) pH, (b) dissolved oxygen, (c) electric conductivity and (d) temperature in the fish tank water (●), inlet (○), outlet concentrations of *I. aquatica* (▼), *L. sativa* (Δ) and *C. glauca* (■) trenches throughout the experiment ($n = 9$ for inlets and $n = 3$ for outlets and fish tank water).

dissolved oxygen, a pH around neutral and low concentrations of ammonia and nitrite (Losordo, Masser & Rakocy 1998). The water quality in this aquaponics system remained fairly constant throughout the experiment (except for slightly increases in EC and phosphorus) and was within the most suitable range for tilapia growth and survival (Popma & Masser 1999; El-Sherif & El-Feky 2009a,b), even though water oxygen concentrations in the culture tanks and in the effluents from the planted biofilters decreased over time because of the increase in fish biomass and accumulation of organic matter in the system (Figs 3 and 4). However, because the effluent of the planted biofilters was aerated by passing the sprinklers on return to the fish tanks, the water oxygen concentration in the culture tanks remained at adequate levels for fish growth (~5.0 mg $L^{-1}$, Fig. 3b). The water temperature increased slightly at the end of the experiment as the last water sampling was conducted in the hottest month of the year. Actually, a better growth rate (1.56% $day^{-1}$) and a lower FCR (1.4 ± 0.4) was observed in the present study than generally reported in other studies (Cruz & Ridha 2001; Ridha & Cruz 2001; El-Shafai *et al.* 2007b).

Harris (1992) suggested that the ideal size of gravel for plant growth is Ø2–9 mm, which is fine enough to hold sufficient moisture and at the same time allow free-drainage in hydroculture. The vegetable plants in this study were placed in plastic pots filled with gravel and topped with coconut fibre, and the water level in the planted trenches was subsurface. Overall the tested plants grew well without any symptoms of stress. This corresponds to the findings of earlier studies (Trang *et al.* 2010), where *I. aquatica* and *L. sativa* preferred unsaturated growth conditions with the water

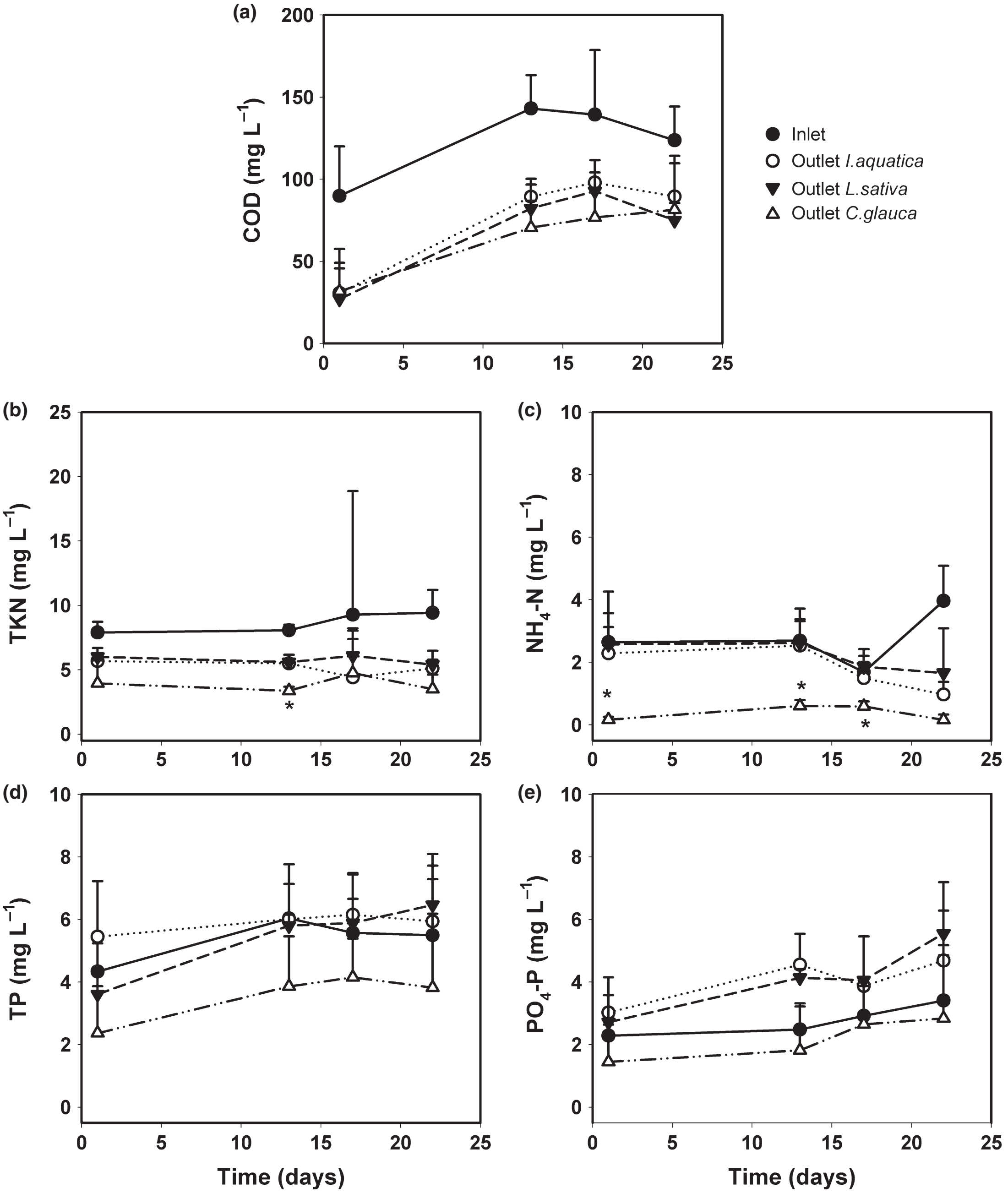

**Figure 4** Mean (±1 SD) inlet concentrations (●) and outlet concentrations of (a) COD, (b) TKN, (c) $NH_4$-N, (d) TP and (e) $PO_4$-P of *I. aquatica* (○), *L. sativa* (▼) and *C. glauca* (Δ) trenches throughout the experiment. Asterisk (*) indicates significant difference between species for outlet concentrations ($n$ = 9 for inlets and $n$ = 3 for outlets).

level below the soil surface. The growth pattern of *I. aquatica* allows periodical harvesting without replanting whereas *L. sativa* must be replanted after harvest. *I. aquatica* can be harvested as soon as 25 days after transplanting. Hence, *I. aquatica* is a better choice to integrate in a recirculating aquaculture system than *L. sativa*. Due to the lower plant densities, the biomass production of both vegetable species was relatively low in the present study compared with the findings in other studies (Seawright, Stickney & Walker 1998; Lennard & Leonard 2004, 2006; Li & Li 2009; Endut, Jusoh, Ali, Wan Nik & Hassan 2010). The harvested vegetables did contribute some – although

**Table 1** Mass balance (mean ± 1 SD, $n$ = 3) of N and P in the integrated recirculating aqua-hydroculture system

| Components | N (g/d) | P (g/d) |
|---|---|---|
| Input feed | 5.7 | 1.5 |
| Incorporated into fish | 2.5 ± 0.8 | 1.1 ± 0.3 |
| Recovered in plants | | |
| *I. aquatica* | 0.1 ± 0.0 | 0.02 ± 0.00 |
| *L. sativa* | 0.003 ± 0.002 | 0.002 ± 0.001 |
| *C. glauca* | 0.3 ± 0.1 | 0.1 ± 0.0 |
| Sludge removed | 0.04 ± 0.03 | 0.02 ± 0.01 |
| Accumulated in water | 0.2 ± 0.1 | 0.1 ± 0.0 |
| Unaccounted for | 2.5 | 0.1 |

only 4% – additional income from the integrated recirculating aqua-hydroculture system, when the value of the harvested vegetable biomass was capitalized based on current market prices. *Canna glauca* grew vigorously throughout the study with a biomass production that was more than five times higher than that of *I. aquatica*, and hence also a high nutrient uptake rate of 0.14 g N and 0.05 g P $m^{-2}$ $day^{-1}$. The fact that *C. glauca* can be harvested repeatedly is an advantage. Although *C. glauca* does not have a market value, it enhances the aesthetics of the system by its beautiful flowers. Also other species of *Canna* (*Canna* × *generalis* Bailey L. H.) have been successfully used to treat domestic wastewater with high aboveground biomass productions of 3128 g dry mass $m^{-2}$ $year^{-1}$ (Konnerup, Koottatep & Brix 2009).

The removal of COD in the plant trenches did not differ between the plant species. $NH_4$-N was removed efficiently in the plant trenches, particularly in the trenches with *C. glauca* (Fig. 4c). The mass balance calculation, however, showed that plant uptake of N and P constituted only a fraction of the amount removed from the water, indicating that coupled nitrification–denitrification processes in the root zone of the plants and in the gravel substrate were probably significant. Phosphorus removal was less efficient compared with N removal. Particulate P was removed by the plant trenches, but $PO_4$-P accumulated over time in the water because of degradation of organic P.

Rakocy *et al.* (2006) reported that the variations in the nutrient concentrations of the recirculation water were caused by three factors: nutrient excretion from the fish, nutrient taken up by plants and addition of tap water to compensate for water lost by evaporation. In the present study, approximately 45% of N and 76% of P in the input feed were incorporated in the fish meat. This addition was significantly higher than that in the study of Rafiee and Saad (2005), who reported that red tilapia captured an average of 32.5% N and 15.9% P of input feed during a 3-week culture period. Solids removal from the fish tanks is an important component of the water quality management in recirculating aquaculture systems, but in our study the amount of sludge that could be removed from the tanks was very small and constituted only 2 and 3% of the N and P loading respectively. The plants took up only 6 and 7% of the N and P in the feed, respectively, and the accumulation of N and P in the recirculated water was negligible. The remaining unaccounted-for in the balance (45% N and 9% P) was presumably bound in solids and biofilms on the gravel and lost by denitrification. Steen, Brenner and Oron (1998) reported that 18% of influent N was recovered by duckweed and 8% settled in sediment. El-Shafai, El-Gohary, Nasr, Steen and Gijzen (2007a) found that 80% of N was taken up by duckweeds (*Lemna gibba* and *Lemna minor*), 5% was settled in sediments and 15% N was unaccounted for. In a study on reusing catfish effluent for rice cultivation, the rice crop removed 32% N and 24% P from the effluents (Lin & Yi 2003). Thus, the importance of plant uptake and other removal processes varies between studies primarily because of differences in the ratio between fish production and plant production. The present system could be improved by having a larger ratio between plant production and fish production.

The water use efficiency of the integrated aqua-hydroculture system was high as the system was running for 50 days without water renewal. Tap water was added throughout the study to compensate for the water lost by evapotranspiration and water sampling. The amount of water needed (approximately 1 $m^3$ per kg of fish produced) is, however, negligible compared with the amount, 189 $m^3$ water was used to produce 1 kg fish, reported for conventional fish pond culture (Nhan *et al.* 2008). This underlines the high water use efficiency of integrated recirculating aqua-hydroculture systems (McMurtry, Sanders, Cure, Hodson, Haning & St Amand 1997).

## Conclusions

This research demonstrates that aquaponics has the potential to significantly reduce the need for freshwater and at the same time provide the farmers with an extra income from the plant production. As the vegetable and ornamental flower species used in the study performed very differently in the hydroculture system, more studies are needed to optimize plant selection and growth conditions. Also, our study was carried out for a short period of 50 days and the fish did not reach market size. Longer term and larger scale studies are needed to evaluate the system's potential as an applicable technique for the commercial aquaculture industry in the Mekong Delta.

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