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Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production

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Abstract

This chapter describes the possibility to combine wastewater treatment in recirculating aquaculture systems (RAS) with the production of crop plants biomass. In an aquaponic RAS established in Waedenswil, Zurich, the potential of three crop plants was assessed to recycle nutrients from fish wastewater. A special design of trickling filters was used to provide nitrification of fish wastewater: Light-expanded clay aggregate (LECA) was filled in a layer of 30 cm in vegetable boxes, providing both surface for biofilm growth and cultivation area for crop plants. Aubergine, tomato and cucumber cultures were established in the LECA filter and nutrient removal rates calculated during 42–105 days. The highest nutrient removal rates by fruit harvest were achieved during tomato culture: over a period of >3 months, fruit production removed 0.52, 0.11 and 0.8 $g\,m^{-2}\,d^{-1}$ for N, P and K in hydroponic and 0.43, 0.07 and 0.4 $g\,m^{-2}\,d^{-1}$ for N, P and K in aquaponic. In aquaponic, 69% of nitrogen removal by the overall system could thus be converted into edible fruits. Plant yield in aquaponic was similar to conventional hydroponic production systems. The experiments showed that nutrient recycling is not a luxury reserved for rural areas with litlle space limitation; instead, the additionally occupied surface generates income by producing marketable goods. By converting nutrients into biomass, treating wastewater could become a profitable business.

Keywords: Aquaponic; Nutrient recycling; Nutrient removal; Trickling filter; Biomass production

1. Introduction

Trickling filters offer well-known and widely applied technical solutions to treat wastewaters of different sources and compositions. Their main purpose is to provide nitrification and removal of Biochemical Oxygen Demand (BOD) [1]. Treatment capacity is related to the total surface of the filter medium, providing area for bacterial growth. As each filter medium has a specific index of area per volume, the treatment capacity can be indicated as mass removal per volume per time.

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Unfortunately, the conventional trickling filter approach does not recycle nutrients in the wastewater but merely transforms them into non-toxic (H_2O, NO_3) or gaseous forms (CO_2, N_2) [2].

We studied the possibilities of combining wastewater treatment in constructed wetlands with the production of crop plants biomass. The idea was to use the surface of trickling filters to grow crop plants, to combine the processes of nutrient transformation (mainly nitrification) and nutrient recycling. The original concept was established by aquaponic producers [3,4], which achieved remarkable fish to plant production ratios in market-scale production systems. For each kilogram of fish produced in feedlot aquaculture, the nutrients in the resulting wastewater allowed a vegetable biomass production of 7 kg [5].

Merging the two disciplines, wastewater treatment and crop production, requires moving the focus from optimizing the degradation, nitrification, denitrification and absorption rates to maximizing the recycling rates of phosphorus and nitrogen and to fulfilling the quality requirements of the resulting products such as plant biomass and effluent water.

In contrast to bacterial degradation, nutrient assimilation by plants is limited by surface, as photosynthesis is dependent on solar radiation. Therefore, to achieve maximum nutrient recycling rates, trickling filter systems should provide a large surface area for plant growth and photosynthesis in relation to their volume. In theory, a planted trickling filter could double its nutrient recycling capacity when constructed halve as deep and with a surface twice as large. Given this, possible applications of the concept would not be in the classic wastewater treatment disciplines where land use is regarded as loss of efficiency, but rather in industry sectors already using large surfaces for plant production. In other words, the idea is not to replace existing filter techniques in municipal wastewater treatment but to recruit producers of hydroponic vegetables as recipients and users of nutrient-rich wastewaters. This approach reflects postulations that suggested to re-integrate agronomic production forms nowadays separated in monocultures to combined production systems [6].

This study describes one possible application of this concept: planted trickling filters adapted to provide nitrification in recirculating systems for fish production. This combination of fish and plant production in an integrated recirculating system is called aquaponics [7]. Many different system concepts are feasible, depending on the target crops or resources available [8]. Our research focused on the selection of crop plants characterized by high productivity and thus nutrient recycling capacity. To test the suitability of the new combined production system for vegetable producers, we compared plant productivity in aquaponic and in conventional hydroponic systems.

Microbiological contamination of the target plants is not a problem discussed in aquaponic literature, as the harvested crops have only contact with the fish water by their root system. Nevertheless this topic should be addressed, as heterotrophic plate counts revealed similar concentrations in salmonid farm effluent (10^5 CFU/ml [9]) as in mechanically pre-treated municipal wastewater (10^6 CFU/ml [10]). In case hydroponics are used to recycle nutrients from municipal wastewaters, this topic is of primary importance. In this case, pre-treatment with planted sand filters followed by UV radiation should be considered [11]. This approach was already tested; lettuce and capsicum indeed are able to utilize nutrients from municipal wastewaters [12].

2. Materials and methods

2.1. Aquaponic system

Aquaponic is a special form of recirculating aquaculture systems (RAS), namely a polyculture consisting of fish tanks (aquaculture) and plants that are cultivated in the same water circle (hydroponic) [3–5]. The primary goal of aquaponic is to reuse the nutrients released by fishes to grow crop plants. Most systems separate fish faeces as quickly as possible to reduce the BOD load in the RAS, to enhance nitrification performance and to reduce clogging of plant roots, which could lead to loss of crop productivity.

Our aquaponic system established in Waedenswil, Zurich, was a new concept using light-expanded clay aggregate (LECA™) [13] as filter medium for the trickling filter. LECA is a type of clay, which is super-fired to create a porous medium. It is heavy enough to provide secure support for the plants' root systems and was used in indoor and outdoor hydroponic systems [13–17]. LECA was filled in standard boxes (0.4 × 0.6 × 0.4 m, green PVC), aligned in three rows in an adjoining greenhouse (Fig. 1). In total, 74 boxes were used, holding 3.0 m^3 of LECA.

A primary goal of the system was to test a completely closed RAS, making use of fish faeces, too. The raw effluent from the 2.5 m^3 fish tank (2 × 2 m square, water depth 0.65 m, green fibre glass with central outlet at the bottom) was pumped and distributed in the LECA filter at a rate of 10–15 $m^3\,h^{-1}$ with a specially developed irrigation system. To achieve a homogenous load of Total Suspended Solids (TSS) distribution to the plant boxes, standard sewage piping (*d* = 0.11 m, orange PVC) was levelled horizontally over the LECA rows and each box irrigated through a drilling hole of 6 cm diameter. The water exchange rate was set to zero, and the system was operated as a closed looped system. Only evaporation water was replaced with tap water. Technical details were described only in an unpublished report so far [18].

Fish species cultivated were tilapia (*Oreochromis niloticus*) during aubergine production in 2004 and eurasian perch (*Perca fluviatilis*) in the later experiments with tomato and cucumber. Tilapia was a natural strain imported from Lake Turkana, Kenya, perch was obtained from Percitech S.A., a Swiss company specialized in perch breeding. The fish were fed *ad libitum* with a swimming pelleted feed (Trouvit Tilapia Starter, 3.5 mm, 45% raw protein).

As a control, a row of 29 boxes in a hydroponic system was installed, holding 1.2 m^3 LECA (Fig. 2). Tap water was pumped from a separate 0.3 m^3 water reservoir at a rate of 5 $m^3\,h^{-1}$, and

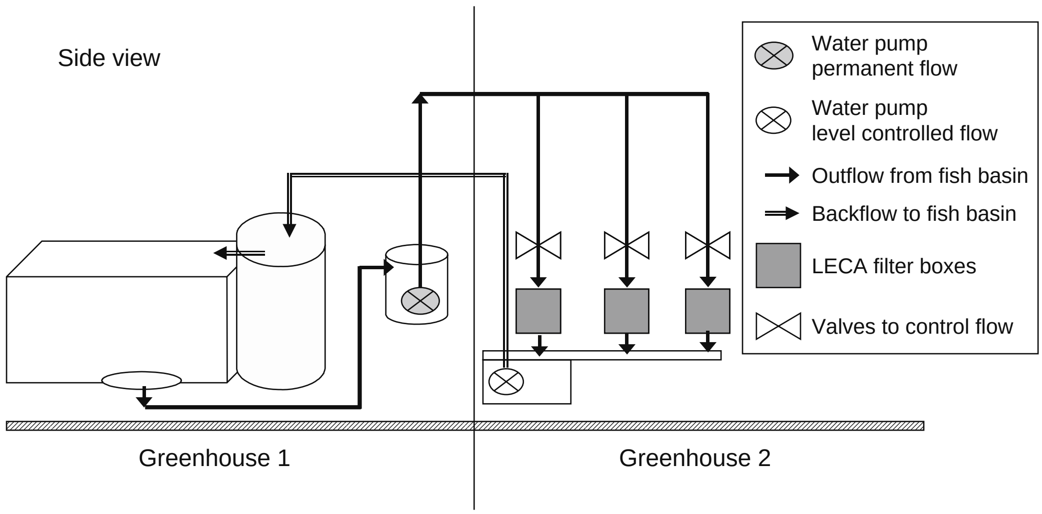

Fig. 1. Aquaponic research unit at Waedenswil, Zurich.

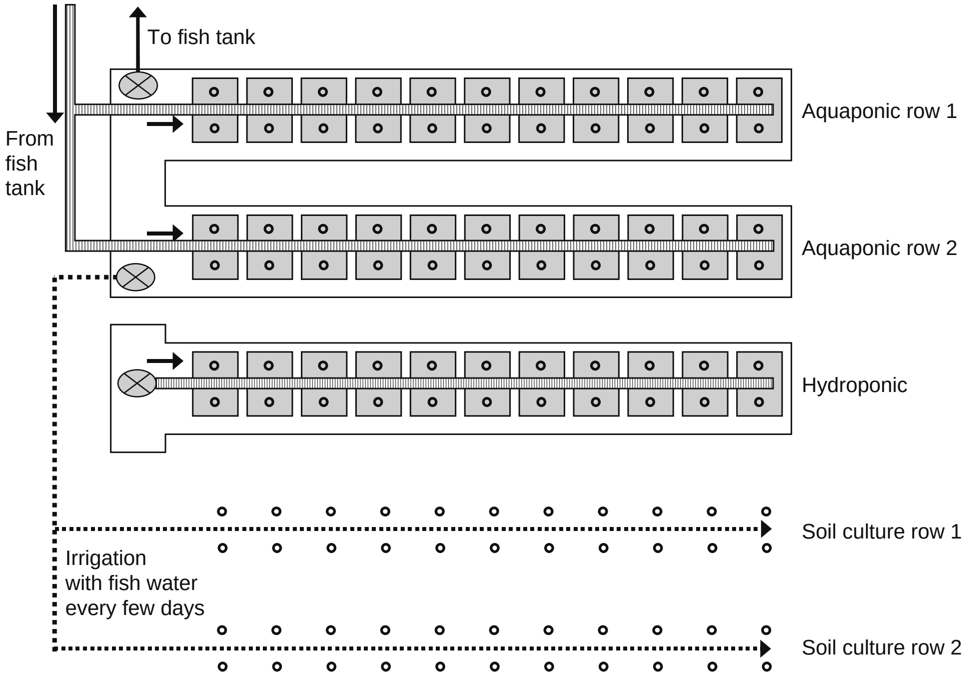

Fig. 2. Plant production in top view with expanded clay boxes (□), water pumps (⊗), plant locations (∘), water collection sheets underneath (▭) and water flows (continuous ⟶ and on demand ····▸).

fertilizer [19] was applied two or three times a week to maintain a fertilizer concentration with an electrical conductivity of 2.5 mS cm^{-1}. This salt concentration was known to be the upper limit for vegetable growth from previous experiments at the institute [20–22]. Evaporated water was replaced continuously, holding the water level constant. During tomato trials, a second control culture was planted in a natural, non-amended soil in the same greenhouse. Soil cultures were irrigated every few days with water from the fish tank, according to the irrigation need of the tomatoes (Fig. 2).

2.2. Nutrient budgeting

As in the recirculation systems the complete water volume passed over the trickling filter once every 20 min, concentration differences between in- and outflow were within detection limits. Thus, samples were taken in the main water reservoir only (fish tank or water reservoir). Input and removal rates were calculated through mass balance, calculated over a specified time interval, by the addition of nutrient input in the form of fish fodder, nutrient removal in the form of fruit and plant biomass harvest, change in the nutrient reservoir in the water, and nutrient losses by water exchange.

Normally, nutrient input would be calculated using the nutrient concentration in the feed, and nutrient incorporation into fish biomass would have to be considered as a sink. Instead, nutrient input was calculated using fertilizer coefficients of the fish feed, which were determined in an experiment with two replicates. Tilapia (25 fish weighing 1330 g and 31 fish weighing 1730 g) were placed in a 220-l glass aquaria, equipped with an unplanted LECA Box as a nitrification filter. Fish were fed with tilapia feed and build-up of nutrients (NH_4, NO_2, NO_3, PO_4, K) measured after 14 days.

2.3. Methods

Electric conductivity, pH, redox potential and dissolved oxygen were either measured continuously and logged every 15 min with SC1000 sensors (Hach Lange sc-sensors 3798-S, phD-S, 1200-S, LDO) or measured daily with a hand-held multi-electrode metre (WTW Multiline 350i). Dissolved ions were determined by photometry (Hach Lange LCK tests, Cadas30).

Plant growth and fruit harvest were assessed weekly according to the criteria established in productive horticulture [22]. The produced biomass was harvested at least at the end of the experiment, and wet weight, dry weight and in some occasions elemental composition of biomass (Carbon, Nitrogen, Phosphorus) were determined. Analyses on tomato biomass were done by Labor fuer Boden und Umweltanalytik in Zurich using Kjehldahl, photometry, Atomic Absorption Spectroscopy (AAS) or Inductively coupled plasma (ICP). For cucumbers and aubergines, values for dry matter and Nitrogen, Phosphorus and Potassium (NPK) content were used from literature [24,25].

3. Results

Tilapia in the aquaria experiment consumed 330 and 436 g feed, respectively. Nutrient release into the water by feeding 1 kg fish feed was calculated to be 46 $\pm$ 4 g N, 6.0 $\pm$ 0.8 g P and 1.0 $\pm$ 0.4 g K.

3.1. Water quality

The trickling filter was efficient and a valuable alternative to a conventional bio filter. All water parameters remained within tolerable limits, except for nitrite which was sometimes above 0.2 mg N l^{-1} during tilapia culture (Table 1). During perch culture, the fish-feeding load was almost halved, thus solving the nitrite problem. Overall, the nitrification capacity of the trickling filter was calculated to be 0.26 kg fish feed m^{-3} LECA d^{-1} [26].

During the three experiments (Table 2), fresh water added to the fish tank was on average 0.445, 1.233 and 0.275 m^3 d^{-1} or 15, 41 and 9% water volume per day. During tomato experiments, a total of 49.17 m^3 or 0.734 m^3 d^{-1} of fish water was used to irrigate the soil cultures, which explains the higher water consumption in the second experiment. Water consumption in the first and third experiment was only due to water evaporation in aquaponic, the lower consumption by cucumbers being related to the production period in late autumn versus aubergine production in summer.

Table 1
Tolerance limits for fish production and range of water quality during the trials with tilapia and perch [17]

Parameter	Unit	Tolerance Limits	Tilapia (Aubergines)		Perch (Tomatoes, Cucumbers)	
			N	Range	N	Range
NH_4-N	mg l^{-1}	<1.0	12	0.03–0.88	13	0.06–0.68
NO_2-N	mg l^{-1}	<0.2	8	0.08–0.57	12	0.01–0.18
NO_3-N	mg l^{-1}	<150	12	1.9–42	13	12.1–95
pH	–	7–8	9	6.8–7.8	7	6.19–7.41
EC	µS cm^{-1}	<1200	9	350–680	9	400–1103
O_2	mg l^{-1}	>6	9	2.6–4.8	4	6.7–7.5

Table 2
Tomato, Aubergine and Cucumber: NPK removal rates by the production systems and recycling by fruits

Plant Species	Start/End	System	Duration (d)	Planted Area (m^2)	Fish Feeding Load ($kg\,d^{-1}$)	Fish Production (kg FW)	Fruit Production		Total System Removal ($g\,m^{-2}\,d^{-1}$)			Fruit Harvest Nutrient Removal ($g\,m^{-2}\,d^{-1}$)			Nutrient recycling (%)		
							kg FW	g FW $m^{-2}\,d^{-1}$	N	P	K	N	P	K	N	P	K
Aubergine	07.04.2004	Hydroponic	105	5.0	–	–	40.2	82	1.0	0.20	1.3	0.26	0.02	0.2	25	9	16
	19.07.2004	Aquaponic	105	5.0	1.58	88	38.6	90	3.3	0.41	–	0.29	0.02	0.2	9	5	–
Tomato	23.05.2005	Hydroponic	43	2.8	–	–	73.6	389	1.5	0.29	3.0	0.52	0.11	0.8	34	37	28
	29.07.2005	Aquaponic	67	4.9	0.89	27	116.1	355	0.6	neg.	–	0.43	0.07	0.4	69	neg>	–
Cucumber	11.10.2005	Hydroponic	42	4.9	–		25.6	125	0.3	0.06	0.7	0.12	0.03	0.2	36	48	25
	22.11.2005	Aquaponic	42	14.4	0.26	4	48.2	80	0.4	0.07	–	0.08	0.02	0.1	17	27	–

neg. = negative value due to data uncertainties.

3.2. Nutrient removal

The hydroponic system was the same for all the three experiments; the different nutrient removal rates were due to different fertilizer needs of plants (Table 2). The highest nutrient removal rates by fruit harvest were achieved during tomato culture: over a period of more than 3 months, fruit production removed 0.52, 0.11 and 0.8 $g\,m^{-2}\,d^{-1}$ for N, P and K in hydroponic and 0.43, 0.07 and 0.4 $g\,m^{-2}\,d^{-1}$ for N, P and K in aquaponic. In summer 2005, about one-third of NPK removal by the hydroponic system was achieved by tomato fruits. In aquaponic, 69% of removed nitrogen was recycled into tomatoes. For phosphorus, a percentage of more than 100 was calculated, due to the soil irrigation with fish water, where nutrient loss could not be calculated exactly. Tomato showed a higher nutrient recycling capability than aubergine and cucumber (Table 2). For aubergines, nutrient availability was higher due to 78% higher feeding load, but fruit yield from tomato was 201% higher. Cucumber achieved the lowest recycling rates: feed input was lowest, and fruit yield remained moderate as the culture was started late in the year.

Among aubergines, the fruit yields depended mainly on the varieties rather than on the production system. The varieties «Gilo Brasil» and «Red Egg» were by far the best, contributing 28.9 and 25.9 kg, that is 69% of the 78.9 kg overall produced on only a third of the planted area (data not shown).

The reported recycling rates by harvest relate only to marketable production, that is production of edible fruits. The remaining green biomass (plant roots, stems and leaves) was not considered. The total nutrient recycling capacity, including the green biomass, was evaluated with the cucumber model culture. At the end of the culture, the standing crop of green biomass was 68 kg in aquaponic and 24 kg in hydroponic or 141% and 95% of the respective cucumber fruit yield. On account of this, the total nutrient recycling into plant biomass could be doubled, phosphorus recycling approaching ~100% in hydroponic (as intended with a suitable fertilizer) and 50% in aquaponic.

3.3. Vegetable production

Compared with the fertilizer applied in hydroponic, fish water in aquaponic contained factor 3 (nitrogen) up to factor 10 (phosphorus) times less nutrients. Nevertheless tomatoes reached almost identical yields in aquaponic compared with hydroponic or soil cultivation [16]. An important lack in fish water was its low potassium concentration, which was 45 times lower than in hydroponic. This resulted in a poorer tomato quality in aquaponic compared with the other production

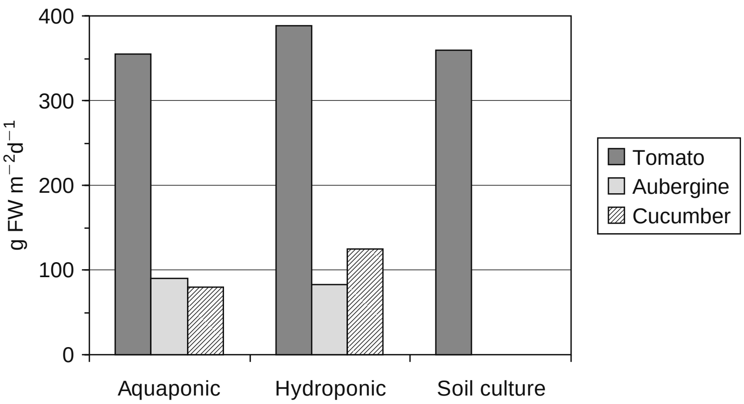

Fig. 3. Fruit yields of tomatoes, aubergines and cucumbers in different production systems [14,15].

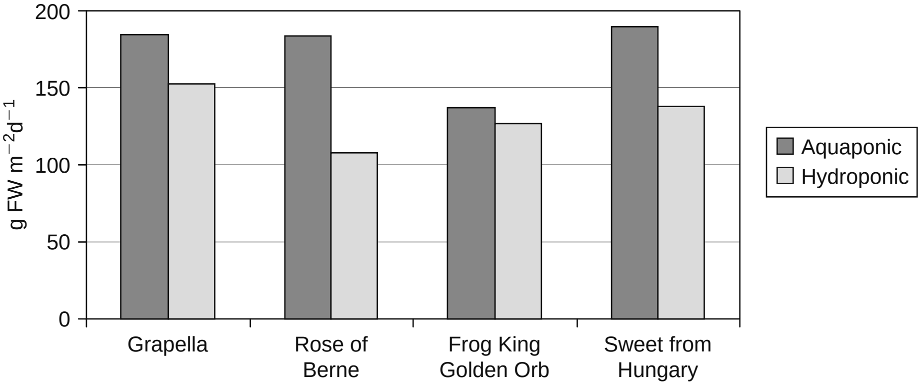

Fig. 4. Fruit yield of tomato varieties in aquaponic and conventional hydroponic [13].

systems. Potassium limitation was reflected by fruit analysis; aquaponic tomatoes contained 22.0 $g\,K\,kg^{-1}$ dry matter versus 40.8 $g\,K\,kg^{-1}$ dry matter in hydroponic.

In an experiment in 2003, different tomato varieties were tested in the same setup [14]. All varieties yielded more fruit in aquaponic, which could be partly explained by the higher water temperature in aquaponic and thus faster initial growth of the plants, leading to earlier ripening (Fig. 4). Tomato yields were generally low because of temperature stress caused by very hot conditions in summer 2003. Sensory assessment of ripe fruits of the variety «Grappella» revealed that 15% of people preferred the taste of tomato grown in aquaponic, 21% the hydroponic type, 47% fruits cultivated in soil and 17% could not detect any differences (n = 19).

4. Discussion

4.1. Fish and vegetable production in aquaponic

Fish production did not differ from typical conventional aquaculture systems with tilapia [4] and perch. The quality of the produced tomatoes however was impaired by a lack of potassium. As potassium is not needed by fish, it is not added to fish feed and thus to the system in adequate amounts. In later experiments, potassium was supplied by adding KOH to stabilize decreasing pH values due to permanent nitrification. Tomato yield equalled productivity in traditional soil cultures but was significantly lower than in intensive soil-less cultivation. With respect to the nutrient recycling capacity, aquaponic systems could nevertheless be profitable for vegetable producers. It was shown before through computer modelling that combining aquaculture and traditional agriculture increases income while minimizing production risks [27]. In Australia, several companies are already applying the technique and are serving the market with produce [5].

4.2. Nutrient recycling rates

These reported removal rates are comparable to those achieved in constructed wetlands treating municipal wastewater, where numbers in the range of 250–630 $g\,N\,m^{-2}\,a^{-1}$ and 45–75 $g\,P\,m^{-2}\,a^{-1}$ were reported [28]. The same study estimates that through harvesting of aboveground vegetation, 100–200 $g\,N\,m^{-2}\,a^{-1}$ and 10–20 $g\,P\,m^{-2}\,a^{-1}$ could be removed, thus achieving recycling rates of 32–40% for TN and 22–27% for TP. The study states that single-stage constructed wetlands cannot achieve high removal of total nitrogen due to their inability to provide both aerobic and anaerobic conditions at the same time. Our findings show that it is possible to achieve high nutrient removal rates while recycling nutrients using aerobic trickling filter systems. Instead of maximizing the denitrification potential of wastewater treatment systems, we propose to consider nitrogen as a valuable resource that should be converted into crop biomass.

4.3. Trade-off between filter volume and surface

Removal of pollutants is related to filter medium volume, whereas nutrient uptake and assimilation into plant biomass is based on filter surface exposed to sunlight. The surface-to-volume ratio defines the maximum nutrient recycling capacity of the system. An engineer designing a filter system is forced to choose between high specific removal rates on little space and nutrient recycling potential requiring a larger space. Is nutrient recycling a luxury only achievable in rural areas, where space limitation is a lesser problem than in urban environments? At the point where the additionally required surface generates income by producing marketable goods, higher infrastructure spending to improve nutrient recycling capacity is no luxury any longer. Our experiments showed that this can be achieved using aquaponic systems, with tomatoes providing almost the same fruit yield when irrigated with fish water than with mineral fertilizer. And surprisingly, the fruits do not have any fishy taste.

Studies with constructed wetlands treating municipal wastewater gave hints that there is no benefit in increasing the depth of the treatment beds beyond 0.5 m and that shallower beds may perform better [29]. Beds with a water depth of 0.27 m removed more COD, BOD_5, ammonia and dissolved reactive phosphorus than beds with a depth of 0.5 m [30]. These findings may encourage opting for shallower treatment beds, where the nutrient recycling potential of plants can be better utilized.

5. Conclusions

The designed trickling filter systems with LECA were able to treat the fish wastewater in RAS adequately, while providing growth area for crop plants. The integrated system produced both fish and vegetables (aubergine, tomato, cucumber) suitable for human consumption. Additional experiments showed that also industrial hemp, roses [14] and herbs (basil, parsley) can be successfully cultivated in aquaponic.

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References

[1] W. Gujer (Ed.), *Siedlungswasserwirtschaft*, Springer, Berlin, 1999.
[2] D. Kaya, F. Dilek and C. Gökçay, Reuse of lagoon effluents in agriculture by post-treatment in a step feed dual treatment process, *Desalination*, 215(2007), 29–36.
[3] J. Rakocy and J. Hargreaves (Eds.), Integration of vegetable Hydroponics with fish culture: A review. In: *Techniques for Modern Aquaculture, Proceedings of Aquaculture Engineering Conference, Washington*, 21–23 June 1993.
[4] M. Timmons, J. Ebeling, F. Wheaton, S. Summerfelt and B. Vinci (Eds), *Recirculating Aquaculture Systems, Northeastern Regional Aquaculture Center*, Cayuga Aqua Ventures, New York, 2002.
[5] G. Wilson, Australian barramundi farm goes aquaponic, *Aquaponics Journal*, 37(2005), 12–16.
[6] G. Oomen, E. Lantinga, E. Goewie and K. Van der Hoek, Mixed farming systems as a way towards a more efficient use of nitrogen in European Union agriculture, *Env. Pollution*, 102(1998), 697–704.
[7] J. Rakocy, M. Masser and T. Losordo, *Recirculating Aquaculture Tank Production Systems: Aquaponics – Integrating Fish and Plant Culture*,

Southern Regional Aquaculture Center Publication #454, http://srac.tamu.edu/getfile.cfm?pubid=105.
[8] S. Diver, *Aquaponics – Integration of Hydroponics with Aquaculture*, 2000, www.attra.ncat.org.
[9] A. Bomo, A. Husby, T. Stevik and J.K. Hanssen, Removal of fish pathogenic bacteria in biological sand filters, *Water Research*, 37(2003), 2618–2626.
[10] K. Sleytr, A. Tietz, G. Langergraber and R. Haberl, Investigation of bacterial removal during the filtration process in constructed wetlands, *Science of The Total Environment*, 380(2007), 173–180.
[11] D. Abdessemed, G. Nezzal and R. Aïm, Treatment of wastewater by ultrafiltration, *Desalination*, 126(1999), 1–5.
[12] B. Boyden and A. Rababah, Recycling nutrients from municipal wastewater, *Desalination*, 106(1996), 241–246.
[13] O. Lekang, Efficiency of nitrification in trickling filters using different filter media, *Aquacultural Engin.*, 21(1999), 181–199.
[14] D. Wenger, Produktion von Rosen und Tomaten in einem Polykultursystem mit Fischabwasser, Diploma Thesis, Hochschule Waedenswil, 2003.
[15] L. Frei and Ch. Nenniger, Vergleich von Auberginen-Sorten in Aquaponic-Hydroponic Systemen, Term Thesis, Hochschule Waedenswil, 2004.
[16] F. Hirsch, Ertragsentwicklung der Tomatensorte «Aromata F1» in Aquaponic, Hydroponic und Bodenkultur, Term Thesis, Hochschule Waedenswil, 2005.
[17] A. Graber and D. Todt, Integrierte Fisch- und Pflanzenproduktion in Aquaponic, *Deutscher Gartenbau*, 16(2004), 36–37.
[18] A. Graber, Egliproduktion in Aquaponic – Technische Machbarkeit, Unpublished Project Report, Hochschule Waedenswil, 2005.
[19] Grodan newsletter, www.grodan.de, Grodania A/S Hovedgaden 501 2640 Hedehusene, Denmark.
[20] J. Staudenmann and R. Junge-Berberovic, Treating biogas plant effluent through aquaculture: First Results and experiences from the pilot plant Otelfingen (Switzerland). In: B.B. Jana, R.D. Banerjee, B. Guterstam and J. Heeb (Eds.), *Waste Recycling and Resource Management in the Developing World, University of Kalyani*, India and Int. Ecol. Eng. Soc., Switzerland, (2000), 51–57.
[21] J. Staudenmann and R. Junge-Berberovic, Recycling nutrients from industrial wastewater by aquaculture systems in temperate climates (Switzerland), *Journal of Applied Aquaculture*, 13(2003), 67–103.
[22] A. Graber and R. Junge-Berberovic, Wastewater-fed aquaculture otelfingen, Switzerland: Influence of system design and operation parameters on the efficiency of nutrient incorporation into plant biomass. In: J. Vymazal (Ed.), *Wastewater Treatment, Plant Dynamics and Management in Constructed and Natural Wetlands*, Springer Verlag, 2008, 299–310.
[23] G. Vogel, *Handbuch des speziellen Gemüsebaus*, Ulmer, Stuttgart, 1996.
[24] G. Hochmuth, D. Maynard, C. Vavrina, E. Hanlon and E. Simonne (Eds.), *Plant Tissue Analysis and Interpretation for Vegetable Crops in Florida*, 2004, http://edis.ifas.ufl.edu/EP081
[25] S. Yoshida, M. Kitano and H. Eguchi, Growth of cucumber plants (*cucumis sativus* L.) under diurnal control of air temperature, *Biotronics*, 27(1998), 97–102.
[26] N. Gnauck, Nitrifikation in Aquaponic, Term Thesis, Hochschule Waedenswil, 2005.
[27] J. Bacon, C. Gempesaw, I. Supitaningsih and J. Hankins, Risk management through integration aquaculture with agriculture. In: J.K. Wana (Ed.), *Techniques for Modern Aquaculture, Proceedings of an Aquacultural Engineering Conference*, 21–23 June 1993.
[28] J. Vymazal, Removal of nutrients in various types of constructed wetlands, *Science of The Total Environment*, 380(2007), 48–65.
[29] T. Headley, E. Herity and L. Davison, Treatment at different depths and vertical mixing within a 1-m deep horizontal subsurface-flow wetland, *Ecol. Eng.*, 25(2005), 567–582.
[30] J. Garcia, P. Aguirre, R. Mujeriego, Y. Huang, L. Ortiz and J.M. Bayona, Initial contaminant removal performance factors in horizontal flow reed beds used for treating urban wastewater, *Water Res.*, 38(2004), 1669–1678.