The Need for Systems Design for Robust Aquaponic Systems in the Urban Environment

T. Vermeulen
Wageningen UR Greenhouse Horticulture
Bleiswijk
The Netherlands

A. Kamstra
Wageningen UR Imares
IJmuiden
The Netherlands

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Abstract

Aquaponics – the co-production of fish and plant products – is gaining interest both by entrepreneurs and researchers. This article evaluates both the technical setup as well as the economic potential of aquaponic systems and is aimed at identifying relevant knowledge questions for further improvements. Using system requirements for hydroponic systems and aquaculture, the aquaponic system was compared to a typical Dutch rockwool system. Aquaponics was found to be an improvement on current practices when using Deep Flow Technique (cultivation in a flowing thick water layer), resulting in better nutrient availability for the plants and re-use of nitrate. However, the technical challenges of the direct linkage between the two production systems in terms of needed technology and disease management was found to make the total system suboptimal when compared to conventional practices. The technological advantages of efficiency in use of land and energy and re-use of nutrients were found to be a marginal cost reduction of 1.2%. The article concludes that the added value of aquaponics can be found in the total business concept of producing in an urban environment with direct relationship with consumers. Further improvement of aquaponics can be found in improved disease management of the system – through management or improved design.

INTRODUCTION

Urban farming creates value through the production of small scale, sustainable and local produce, often in direct interaction with the consumer. Sustainability is achieved through the re-use of waste streams of water, nutrients and energy by combining different (agricultural) activities. A sustainable, applicable and small scale system for such re-use is the combination of fish production in Recirculating Aquaculture Systems (RAS) and horticulture – so called Aquaponics. For professional aquaponics to take off in Europe the production systems need to have added value, be robust and easy to use. Research has focused on plant aspects (nutrients and quality; Pantanella et al., 2012) and fish production (densities, diseases) and technology. But less on the business rationale and design structure. However, designing for such complex systems requires a systematic approach, where an analysis of functions and quantified requirements is used to select and improve on the technical lay-out. Functions and requirements are based on insights and needs from both researchers and experts as well as users and stakeholders – in the case of urban farming city planners and the general public. However, such analysis has only recently been developed for both hydroponic systems and aquaculture, but not for the combination of the two nor the application in an urban setting. This paper describes the system requirements for both aquaculture as well as horticulture that would apply for aquaponics in an urban environment.

SYSTEM TO BEAT

For aquaponics to be developed in the northwestern European context, it will have to compete with the current food system for fresh produce. The development of the horticultural cluster in the North-West of Europe has resulted in the availability of fresh produce at relatively low price at close proximity. The logistical systems allow for fresh stock being delivered multiple times a day at local supermarkets. Likewise the logistical hub of harbours like Rotterdam, Antwerp and Hamburg make it possible to supply mainland Europe with frozen fish from all over the world, while marine fish is caught locally or imported through these same harbours. Development of aquaculture in RAS has been slow and difficult (Martins et al., 2010). Table 1 showed that at high production levels the current agricultural system is able to produce at low costs. Largest contributors to the costs in horticulture are the costs for energy, labour and investment (land and facilities).

PROMISE OF AQUAPONICS

In order for aquaponics to be a profitable solution to current northern European agriculture and aquaculture sector, the system has to be better at reducing costs and/or delivering added value. Where cost reduction is relatively easy to calculate, value adding can be viewed as a product-characteristic (taste, appearance, traceability), a logistical benefit (volume, just in time, local) or a (paid) societal value.

On-farm integration of aquaculture with other agriculture production systems has a long tradition in Asia (Prein, 2002) and comes world-wide in many different varieties. Recently, the application of Integrated Multi Trophic Aquaculture (IMTA) in modern fish farming is studied seriously (Bunting and Spighel, 2009). Aquaculture in closed systems (RAS) has developed strongly during the last decades (Martins et al., 2010). This production system is ideally suited for urban environments (Costa Pierce, 2005). RAS produces a relatively small flow of nutrient rich effluent which can technically be utilised in a hydroponics production system. From an environmental point of view, the integrated system is seen as more sustainable through the re-use of nutrients (N and P), the higher efficiency in use of land and energy. Technically it promises a local, robust and smart-tech solution to fresh produce, while economically it is presented as a viable system (Rakocy, 1999; Rupasinghe and Kennedy, 2010; Seawright et al., 1998).

DESIGN APPROACH

Aquaponic systems need to meet well the requirements of both the crops as the fish, and the added requirements for joining the two. Using design approaches earlier developed for production systems (Kroonenberg and van den Siers, 1999; Van Henten et al., 2006) first drafts of systems can be made and evaluated on paper. These approaches apply a systematic definition of requirements, functions and quantified evaluation criteria for the system. Using these quantified criteria a design can be evaluated. For the separate systems of horticulture and aquaculture as well as the combination of the two aspects, crucial system requirements and evaluation criteria are given in Table 2. The requirements and criteria are a set of optimal and critical values for production factors for both crop and fish. The table shows quantified values such as minimal O_2-concentrations in the water basins as well as indicators that are species specific and require further quantification.

Optimisation of aquaponic systems has been achieved over the past years through 1) applying Deep Flow Technique (DFT – systems with a water level generally more than 5 cm deep, with the water kept in circulation, while plants float on the water in styrofoam plates or otherwise held in position) for the crop production and 2) availability of other fish species apart from tilapia. Deep flow systems buffer imbalance in the nutrient solution through the larger quantity of nutrient solution per plant than in other systems. The roots are replenished continuously as opposed to substrate systems where refreshment of the root zone is limited by the water holding capacity of the substrate. Because of the ability of delivering high yields using a sub-optimal nutrient solution, the development of Deep Flow systems has been more beneficial for aquaponic systems than conventional hydroponic systems. Recent findings in the positive effect of keeping the plant base above the water level (made commercial through concepts like 'Dry Hydroponics'; Cultivitation Systems, 2012) make it possible for more herbaceous plants to grow on deep flow. Optimisation of crop rotation has been shown to be an important tool in nutrient utilisation (Adler et al., 2003).

The optimisation in fish farming has been focused on selection of new species for land-based aquaculture and improvement of water treatment systems in RAS. Species like catfish, eel and percids were found to do well in recirculating systems. These new species make aquaponics more productive, but do not differentiate between aquaponics and conventional aquaculture.

The conventional systems for RAS and substrate-based horticulture as well as an optimised aquaponic system can be scored using the quantified evaluation criteria presented in Table 2. Based on the scores of the components of the production systems as well as interpretation on the aspects of joining the two, an evaluation is performed using scores of -2 (system is technically unviable based on this requirement), -1 (system performs sub-optimal for this requirement), 0 (system is acceptable – compared to soil bound production), 1 (system produces better than soil bound), 2 (this aspect is not a limiting factor for productivity in this system). The interpretation is given in Table 3. For the horticultural side, the deep flow used in aquaponics scores better than conventional rockwool-based production on refreshment of the nutrient solution in the root zone, but lower in terms of disease management through prevention of bacterial formation. On the fish-side, aquaponics improves on conventional RAS be re-use of the nutrients. For the other system requirements the systems are evaluated equal. In general the components of aquaponic to be technically competitive compared to conventional soilless cropping systems and aquaculture. However, the direct linkage of aquaculture and horticulture leads to low scores. In terms of disease management, system efficiency and extra technology needed, aquaponics is less effective than separate production systems. Current disease management practices require the system to be (temporarily) non-recirculating and effectively temporarily an open system (Priva, 2009).

This technical analysis does not include the knowledge requirement of the users and the logistical challenges on company level.

BUSINESS ASPECTS

Despite technical challenges aquaponics is internationally very popular in terms of exposure in the media and initiatives that are looking into realising it. This can either be explained by direct cost benefits of the promises of sustainability or by understanding the total business concept of companies that employ the system.

The promises of sustainability include closing nutrient and energy cycles. However, Schram et al. (2001) calculated a cost reduction of only 0.6% for re-use of nutrients, 0.29% reduction for more efficient use of heat and 0.28% for CO_2-exchange. They concluded the cost reduction did not outweigh the challenges of developing a new production principle. Rupasinghe and Kennedy (2010) calculated an improvement of the net present value of 4.6% in an integrated aquaponic system of lettuce and barramundi.

The value of aquaponics can also be stated in terms of cost of land and as a solution to environmental issues. Having plant production on top of a fish pond will reduce land costs of investment of 5-25 € per m^2 (depending on location), resulting in cost reduction of 1.5-7%. Tests with such set-up concluded that combining the systems hinder the production management practices and make the total system not efficient. The potential added value of aquaponics as a solution to environmental problems also does not hold, since aquaponics is not able to clean waste water from the horticulture side (Na-rich water containing nutrients and possible pesticide residues), while fish waste water – mainly P – in conventional RAS can be sustainably dried, solidified and put to use elsewhere. Nitrification remains as a direct cost saver in aquaponics, but as operational costs for nitrification vary from 0,10 to 0,30 €/kg production in eel farms (Kamstra et al., 1998).

Placing aquaponics in a total business concept however, paints a different picture. Based on interviews with current users, the advantage of aquaponics is in its ability to produce fresh produce in the vicinity of consumer and its charm in displaying the production to these consumers. The aspects of small scale production, direct sales and close interaction with consumers make aquaponics a welcome feature for companies that use direct sales, like in urban agriculture. Urban agriculture – or urban farming – is the local production of food to supply the local communities. This agriculture approach understands the need for consumers to be (re-)connected and if possible involved in their own food production. Larger cities all over the world are looking into the potential of using urban farming concepts for maintaining green and healthy living environments.

CHALLENGES AND OPPORTUNITIES

Using the quantitative technical requirements of a design approach to evaluate the current aquaponic systems to conventional fish (RAS) and crop practices, aquaponics seems a suboptimal production system. The perceived environmental benefits of nutrient re-use, energy efficiency and land use seem only marginally cost-effective and diminished by sustainable practices in conventional systems, while not delivering higher yields. Aquaponics therefore only marginally deliver on its promises of economic and environmental benefit. Aspects of possible differences in product quality and societal value have not been taken into account. This design approach identifies the higher technological challenges (filter- and re-use systems) and the challenges of disease management as key aspects that need further improvement. Future research should be focused on understanding mechanisms of disease management (resilience?) within the water basins for both healthy fish and plants, while systems development needs to simplify and reduce the costs of the technology need for the direct linkage of plant and fish production.

From a business perspective, current aquaponics seems uncompetitive with conventional (rockwool) production and RAS-systems. The added value of aquaponics is likely to be found in a total business concept, where the visibility of production of fish and crops is used to improve interaction with and among consumers, resulting in high-margin sales. Such business concepts can be found in an urban setting, where consumers can interact with the grower/farmer and gain understanding of the dynamics of food production in a closed system. Again, understanding of disease management seems vital to maintain a closed system and deliver produce in acceptable quality and quantity.

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Tables

Table 1. Production figures for main vegetables and fish in current Dutch production systems (P. Vermeulen and A. Kamstra, pers. commun.).

System	Crop	Productivity (unit/m^2/y)	Production costs (€/unit)
Soilless	Tomato	34-65 (kg)	0.85-1.85
	Pepper	35 (kg)	1.60
	Cucumber	200 (cucumbers)	0.28
Soil bound	Lettuce	98 (heads)	0.39
System (RAS)	Fish	Productivity (kg/m^2/y)	Production costs (€/kg)
Fresh water	Eel	200	6.0-8.0
	African catfish	1000	1.1-1.3
	Tilapia	300	1.4-2.0
Sea water	Turbot	50	6.0-7.0

Table 2. System requirements for aquaponic systems.

	Evaluation criteria
Horticulture (root zone) (Blok and Vermeulen, 2012)	
Oxygen supply	Supply at 2,5 mg O_2 per mg fresh root weight per hour
Structure/plant support	Keep plant from falling over
Light tight root zone	No light transmittance to the (nutrient) solution
Uniformity at any plant position	Water circulation at any location in the water basin
Refreshing nutrient solution	System allows for water circulation at least 10 times per day
Prevent un-buffered or un-controlled bacteria formation	Annual rinsing of hoses and cleaning of system
EC, pH-control	Prevent fluctuations (margins in EC, pH, T – crop dependent)
Rain-management strategy (outdoor systems)	Prevent or manage rainfall. In Northern Europe there is an annual surplus of rainfall. This surplus is caused in the (non-productive) winter. Recent heavy downpours in summer will also challenge the water management. Ideally the system is covered, while the rainwater is collected. Under Dutch circumstances a basin of 1500 m^3/ha would be sufficient to use rainwater as the sole water source year-round. (Slootweg and Van Reuler, pers. commun.)
Possibility to clean (steam)	Use materials that can stand 1 hour at 110°C.
Aquaculture (based on setpoints used in Priva, 2009) (tilapia)	
Oxygen supply	6-8 mg/L consumption: 600 g O_2 per kg feed
Uniformity	Continuous flow. Minimum 3 times system content per hour
EC, pH and temp. control	Setpoints: EC 0.5-1.5 mS/cm, pH 6.5-8, T 28±0.5°C
Possibility to clean (steam)	Materials can stand 110°C for 1 hour
CO_2	<2,5 mg/L 15 mg/L
Ammonium (TAN)	<1,5 mg/L
Nitrite	<0.5 mg/L
Nitrate	<500 mg/L
Removal of suspended solids parts	<25 mg/m^3
Aquaponics – extra criteria	
Calculated balance of water and nutrient flows	The dimensions for both the plant and fish production need to be in balance. Both aspects however are crop and fish-specific. The balance in order of magnitude is 1:10-30 fish production (m^3):plant production (m^2) Example: lettuce-barramundi (Rupasinghe, 2010) and tomato-tilapia (Priva, 2009)
Using fish feed and waste water as plant nutrition	Availability of nutrients in plant root zone. Example: NO_3>10 mM (plant specific)
Cross pollution of disease control agents	Common fish disease management with antibiotics, salt (NaCl) and formaldehyde as well as applying plant protection products can only be done through temporal non-recirculation.

Table 3. Evaluation of production systems (score: -2, -1, 0, 1, 2).

Horticulture	Conventional (rockwool, drip irrigation)		Aquaponics (deep flow lettuce, tilapia)	
Oxygen supply	Substrate characteristic	2	High flow rate and active oxygen supply. Still risk of O_2-poor pockets	1
Structure/plant support	Hanging	2	Floating	2
Light tight root zone	Plastic bags over substrate slabs	0	Fully covered basin	0
Uniformity at any plant position	Dripper per plant, vertical drainage	0	High circulation	0
Refreshing nutrient solution	6-10 applications per day	1	Continuous recirculation	2
Prevent un-buffered or un-controlled bacteria formation	Annual cleaning	0	Annual cleaning, but larger compartments and risk of spread of diseases	-1
EC, pH, T-control	At application	1	In actual root zone	2
Rain-management strategy (outdoor systems)	Indoors	2	Indoors	2
Possibility to clean (steam)	Yes	1	Yes	1
Aquaculture (Priva, 2009) (Tilapia)	(Tilapia)			
Oxygen supply	Flow rate - dependent	1	Flow rate - dependent	1
Uniformity	Flow rate - dependent	1	Flow rate - dependent	1
EC, pH and temp. control	In actual production zone	1		1
Possibility to clean (steam)	Yes	0		0
CO_2	Degassing	1		1
Ammonium (TAN)	Biofiltration	2		2
Nitrite	Biofiltration	2		2
Nitrate	De-nitrification	-1	Use as plant nutrients	1
Removal of debris and small floating parts	Filtration	1	Filtration	1
Aquaponics – extra criteria				
Calculated balance of water and nutrient flows			System cannot achieve full efficiency throughout production season	-1
Using fish feed and waste water as plant nutrition			Extra filtering systems needed	-1
Cross pollution of disease control agents			Need for insight in disease resilient systems (insight not yet available)	-2