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Design of an aquaponic system for integrated fish and plant production in Bologna (Italy)

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Abstract

In the short term, an increased role will be played by cities in the decisive shift to create more resilient communities. Aquaponic Design® aims to be part of this change through the design and construction of modular and customizable urban aquaponic systems, fostering public awareness on environmental issues, specifically targeting food production and distribution. By promoting short food chains, reduction of greenhouse gas emissions associated with both transport and packaging, is achieved. In the present study, results from a real environment aquaponic prototype are presented. The growing system, hosted at Le Serre – Kilowatt sustainable food and co-working hub in Bologna, Italy, includes a productive part (230 plants grown in vertical towers) and a table with 12 integrated and communicating mini ponds. The system is also connected with a raised pond (10'000 litres), hosting 400 fishes (including goldfish, koi, medaka and gambusias). Part of the system is accessible to the public and used for demonstrative and training purposes. Preliminary data on productive potential and system resilience are also presented.

Keywords: aquaponic, service design, urban farming, resilient aquaponic system, outdoor/public aquaponic system, vertical farming, soil-less, building reconversion, social agriculture

INTRODUCTION

In the short term, an increased role will be played by cities in the decisive shift to create more resilient communities. The start-up company Aquaponic Design (generated within the framework of the Urban Farm 2019 International Student Challenge, Orsini et al., 2020), aims to be part of this change through the design and construction of modular and customizable urban aquaponic systems, fostering public awareness on environmental issues (Magrefi et al., 2018) and specifically targeting food production and distribution. The general aim of the system is to promote short food chains (Pennisi et al., 2019), toward the reduction of greenhouse gas emissions associated with plant cultivation (Sanyé-Mengual et al., 2018a), post-harvest management and processing of food (Sanyé-Mengual et al., 2018b), while also fostering urban biodiversity and reducing the city ecological footprint (Bazzocchi et al., 2017).

MATERIALS AND METHODS

In the present study, results from a real environment aquaponic prototype are presented. The growing system, hosted at Le Serre – Kilowatt sustainable food and co-working hub in Bologna, Italy, includes a productive part (231 plants grown in vertical towers) and a table with 12 integrated and communicating mini ponds. The system is also connected with a raised pond (10'000 litres), hosting 400 fishes (including goldfish, koi, medaka and gambusias). Preliminary data on productive potential and system resilience are presented. Part of the system is accessible to the public and used for demonstrative and training purposes.

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THE PLANT CULTIVATION SYSTEM

The vertical towers are simplified soilless systems (Gianquinto et al., 2007) made of 90 mm diameter pvc slings. The system is constituted by a total of 21 towers, each being 3 meters high and hosting 11 slots per tower, for a total potential cultivation of 231 plants in less than 4 m^2 of occupied soil. The towers are filled with expanded clay, that provides support to the crops (Savvas, 2003) while also offering additional biofiltration surface. Excess water is discharged into a single underground PVC pipe, which leads to the recollection tank. Thanks to the bio-remediation capacity of the plants, nitrate levels are kept under control, thus also reducing overall water requirements (Goddek et al., 2015). Grown species included lettuce (*Lactuca sativa*), spinach (*Spinacia oleracea*), rocket (*Eruca sativa*), basil (*Ocimum basilicum*), cabbage (*Brassica oleracea* var. *capitata*), chicory (Chicorium intybus), and pak choi (*Brassica rapa* subsp. *chinensis*).

THE FISH REARING UNITS

Fishes were hosted in a main aquaponic tank and an aquaponic table. The aquaponic tank is a rectangular raised iron pond of 10 m^3 water covered with common black pvc cloth. The bottom of the pond is covered with volcanic lapillus, in order to increase the biofiltration surface, while the discharge of the pond is made using the mechanism of the airlift (where water is moved through air pumps), integrated with valves to moderate the flow. It is 12 m long and about 1 m deep.

The aquaponic table is the element that characterizes the entire system and currently undergoing patenting process. It is 12 m long and consists of 12 square PVC-coated mini ponds of different sizes, all connected to each other by the principle of communicating vessels. The table has been designed for recreational purposes and allows those who visit the place to relax or concentrate while sitting comfortably surrounded by marsh plants, colorful flowers of water lilies and irises and occasionally see some goldfish swimming from one pool to another. The water from the table discharges through an overflow into an underground pipe, which also receives the waste water from the pond and leads to the cockpit. The fish species hosted are koi carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*) of various types. These types of fish species have been chosen on the basis of their resistance to climatic factors (Nuwansi et al., 2016), primarily water temperatures close to zero, and their resistance to adverse water quality conditions and low percentage of dissolved oxygen. The body of water was set up in such a way as to mostly recreate conditions experienced in a natural environment, adding floating, submerged and marshy aquatic plants, which would reduce environmental stresses on the fish population. Gastropods such as *Planorbarius* spp. and *Physa marmorata* have also been introduced, because of their detritivore attitude, they represent excellent allies for keeping the aquatic ecosystem clean, improving at the same time the conversion of the organic substance into fertilizer for the plants (Bouwman et al., 2011). The plants used in the pond and in the table have been chosen both as a support to favour a good water quality, in particular during the initial stages of the implementation of the system, and to guarantee shelters for fry and zooplankton. The chosen aquatic plant species (Table 1) were chosen for their resistance to the climatic conditions of the breeding site and specific functionalities.

THE BIOFILTER

The biofilter consists of a 1 m^3 rainwater tank, buried at a depth of about 1.5 m, which collects water from the table, pond and towers. Approximately 500 biocarriers (with 25 mm diameter) were introduced into the tank in order to use the well at the same time as the main biofilter. The tank is also equipped with a floating probe that allows to easily monitor the contained water level and automatically topping up through a 200 L tank that discharges directly into the cockpit, as well as regulating the flow of water entering the pond. Water sensors are also readable through a mobile-app.

Water parameters (pH, KH, NH_3, NO_2, NO_3) were checked every 14 days. Periodical water analyses were conducted in order to allow for a wider understanding of the development of the system and its production potential.

Table 1. Aquatic plants integrated in the system.

Species	Main functions
Coontail (*Ceratophyllum demersum*)	Bioremediation (Keskinkan et al., 2004). Creates many shelters and shaded areas. It is able to absorb nitrites as well as nitrates and has a high oxygenating capacity.
Utricularia spp.	Considered a carnivorous plant because thanks to special sacs it sucks in and digests dead microorganisms. Like demersum, it also has an excellent oxygenating capacity of water (Alkhalaf et al., 2009).
Salvinia spp.	A floating plant, which thanks to its root system is an excellent shelter for both fry and zooplankton (Jayan and Sathyanathan, 2012).
Nynfea (*Pygmaea Helvola*)	A floating plant much loved for its flowers with aesthetic functionality (Kun et al., 2009).
Purple Loosestrife (*Lythrum salicaria*)	A plant with a demerged stem, which produces lilac-coloured flowers; recently gaining interest for its recognised medicinal properties (Tunalier et al., 2007).
Azolla spp	Floating plant with elevate nitrogen fixing potential (Arora and Singh, 2003)
Carex riparia,	Good nitrogen fixing potential (Vymazal, 2013)
Pontederia Cordata,	Good aestheric properties, with intense green lanceolate erect leaves and coloured flowers (Vymazal, 2013)
Cyperus alternifolius	Perennial marshy plant very similar to papyrus and good Nitrogen removal potential (Vymazal, 2013)

RESULTS AND DISCUSSION

SYSTEM FUNCTIONALITY

Once the construction of the system was completed, water was injected and recirculation was activated. Initially, to facilitate the development of the biofilter, inoculations of commercially available nitrifying bacteria were added and a small amount of feed was added to start the nitrogen cycle. At the same time, calcium-based carbonic hardness stabilizers were poured into the water in order to stabilize the pH values and facilitate the development of the biofilm on the tank walls. After the first couple of weeks, with the aim of increasing nitrogen production while avoiding additional straining the bacterial colony, together with the aquatic snails (*Planorbarius* spp and *Physa marmorata*), also zooplantcon such as *Hyalella azteca*, ostracodi and Cyclops were introduced. After about one month, the first goldfish were introduced, for a total of about 1 kg of live weight. By the sixth week, 3 koi carp with an average weight of about 200 g each were introduced. In the eighth week, the presence of the first goldfish fry swimming among the underwater plants was observed. Rapidly afterward, while hundreds of new fish colonised the system, the feeding techniques was modified, moving from a precise calculation based on fish biomass, to a satiated feed (always taking a certain amount of biomass as a reference), supplying different types of feeds alternately 4 to 5 times a day. The pH was kept at levels close to 8, in order to facilitate bacterial proliferation (Table 2). Due to the limited level of nutrients in the water (due to scarce fish population in the initial stages), transplanting of the plants was delayed by 3 months, and this resulted in limited productivity during the most favourable climatic season. During the first cycle, plants presented problems in growth and nutritional deficiencies, in particular nitrogen. Furthermore, as the cold season approached, it was decided not to add additional fishes, postponing any increase of the fish population to the next spring. Indeed, the existing fish population allowed for a constant and gradual increase in nitrates in the water (Table 2), which resulted in a faster and more vigorous growth of the plants placed on the vertical towers (data not shown).

Table 2. Chemical properties of the recirculating water along the season.

Week	NH_4 mg l^{-1} (ppm)	NO_2 mg l^{-1} (ppm)	NO_3 mg l^{-1} (ppm)	Ph	Kh
1°	0	0	0	9	12
3°	0	0	0	9	10
5°	<0,05	0	0	8,5/9	8
7°	<0,05	<0,01	0	8	7,5
9°	0,05-0,1	0,01-0,025	0.5	7,5/8	6 -7
11°	0,1-0,2	0,025	1	8	8
13°	0,05-0,1	0,01-0,025	5	7,5	7
15°	0,05- 0,1	0,01	5	8	7 - 8
17°	<0,05	0	10	7,5 /8	7-8
19°	0	0	10	7 /7,5	6
21°	0	0	10	8	9
23°	0	0	15	8	8
25°	0	0	15	8,5	8-9
27°	0	0	20	8	8
29°	0	0	20	8	8
31°	0	0	25	8	8
33°	0	0	25	8	8

Confirming the successful creation of a small ecosystem, goldfish have reproduced and the fry have managed to survive and grow together with the adults thanks to the abundant presence of submerged vegetation and zooplankton, including cyclops spp., dafnie spp. and *Hyalella azteca*, whose presence was also relevant to improve the diet of adults (Anton-Pardo and Adamek, 2015). During the winter season, altogether with the lower temperature ranges, the metabolism of the fish is reduced. Indeed, during fall 2019, 80 slots of the vertical towers were are kept into cultivation, hosting crops adapted to the cooler weather that is experienced in Bologna, including lettuce, chicory, spinach and cabbage (Orsini et al., 2014). From spring, and whenever the water temperature increases above 18°C, the fish biomass will increase and will allow for a larger surface devoted to plant cultivation (Calone et al., 2019).

THE AQUAPONIC GARDEN AS A MULTIFUNCTIONAL TOOL

Since the aquaponic system was activated (June 15, 2019), elevate interest was observed among users of the space (Sanyé-Mengual et al., 2018b). Interestingly, although the space is open to the public, to date no acts of vandalism were experienced, overall highlighting the general acceptance and recognition of the project (Gasperi et al., 2016). Four dissemination events (with free attendance) were organized, where working principles were illustrated and practical gardening activities were proposed. Out of the 80 participants to the events, around 70% of them did not have any previous awareness about aquaponics. However, all participants were intrigued by the system and considered it valuable to face societal challenges and foster urban farming, confirming that innovative urban technologies for plant cultivation in cities have the potential to foster urban sustainability (Sanyé-Mengual et al., 2019). Building on the results of the awareness creation activities, two workshops (with fee of 30 Euros per person) were organized to a smaller number of participants (around 20), where a small scale aquaponic prototype was implemented. Furthermore, three intensive aquaponic training courses have been carried out, structured as one basic course (2 days, registration fee of 300 Euro per person), and two advanced course (3 days, registration fee of 500 euro per person). Among workshops and course participants, about 80% of the participants started their own aquaponic cultivation at home or within their own agricultural company (e.g. agrotourism), confirming that the adopted learning-by-doing methodologies allowed for a general uptake of the techniques (Ochoa et al., 2019). Accordingly, further dissemination and training events are planned in order to monitor and foster the positive uptake of the innovative technologies among the local community (Sanyé-Mengual et al., 2018c).

SYSTEM CRITICALITY

One of the objectives and challenges of the system, besides ensuring adequate plant growth, is to maximize the welfare of the animals, as goldfish and koi carp, despite the effort for replicating a natural ecosystem, are subject to external and critical stress sources of various kinds. These sources of stress are:

- The material used for building the pond (iron) whose choice was guided by aesthetic reasons expressed by the space managers, but which due to its thermal conduction features leads to problems such as excessive heating of the water especially in summer;
- The exposure of the pond itself to the sun, which radiates throughout the day, heating the iron and consequently also the water temperature. This aspect must be taken into account also in winter when, with sunny days, the temperature could reach and exceed 8 °C, causing temperature changes and therefore inducing possible thermal stresses to the fish population. This may be improved by whitewashing the structures and mounting a roof over the pond, which would result in lower heat absorption associated with solar radiation;
- The presence, particularly in summer, of many people and children, which together can lead to stressful conditions for the animals. Similarly, also the presence of pets and wild animals (e.g. cats and birds) is also a problem, as can also carry fish pathogens. This requires further investigation through appropriate sampling to assess the hygienic health status of the animals.

These criticalities have been extensively discussed with the space managers. They are exacerbated by the double functionality of the space (that stands between production and aesthetic) and the associated free accessibility to the general public.

CONCLUSIONS

After almost 6 months from the start of the system and the dedicated research activities, the citizen participation and active involvement confirms that there is a growing interest and concern about aquaponics also in Northern Italy. Further activities are planned in order to increase awareness of the local population. The constant monitoring of the plant and fish cultivation units will also allow for defining optimal management protocols across seasons. With reference to the recreational functionality, the local users have shown increasing interest and passion toward the system as the season went on, as also observed with reference to the absence of acts of vandalism observed. To conclude, aquaponics in urban environments presents several advantages, not only related to consumption and the environment. It also plays an educational function that combines knowledge of integrated production technologies with low environmental impact in respect of a complex ecosystem.

The maintenance of an optimal balance of plant and animal components plays a key role and represents one of the major future challenges for the expansion of these simplified aquaponics techniques in urban environments.

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