PLEA 2017 EDINBURGH
Design to Thrive

Aquaponic as a System of Building Integrated Food Production

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Abstract: This paper describes the planning parameters to integrate an aquaponic system into a plus-energy house in Austin/Texas. The idea behind this is to close material cycles in the sense of Cradle to Cradle® and to consider existing waste as resources. Therefore, it was examined whether condensation water generated in air conditioning systems (fan coils) can be used to produce food in an aquaponic system. Aquaponics is a technology that combines fish farming and crop cultivation in a circulatory system. In this project, a new aquaponics concept of the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB) is used, which provides individual water circuits for fish and plants, to allow the optimal conditions for fish farming and plant cultivation. The system is placed in a greenhouse. Tilapia were selected as suitable fish. Tomatoes and other crops grow in a "medium based" bed of 3,5 m^2 with a substrate of coconut fibre mats. Thus, about 75 kg of fish and 50 kg of vegetables are produced per year directly at the consumer's place of residence and in a nature-like circulation system.

Keywords: Aquaponic, Sustainable Building, Greenhouse, Water reuse.

Introduction

The impact of climate change calls for special protection of resources on Earth. Water is a particularly valuable resource, as it is the basis of life for man and nature. Reducing water consumption should therefore be targeted. An average American has a daily water consumption of 101.5 gallons (384 litres) in the household. Most of this is used for personal care. Approximately 70% of the water consumption takes place in interior spaces. 30% are used on the garden and outside (City of Philadelphia, 2017). In addition to this direct water consumption, the water footprint also shows the indirect (also known as virtual) water consumption caused by the production and transport of goods. This is where the USA has world's largest. An average American citizen has an indirect water consumption of 2480 m^3 per year. This corresponds to 6,800 litres per day. In comparison, China has an average water footprint of 700 m^3 per capita per year (Hoekstra and Chapagain, 2006).

An integrated aquaponic system offers the possibility to reduce both, direct and indirect water consumption. The use of recycled water avoids additional water consumption from the public drinking water supply. The hydroponical cultivation method is twice as efficient in water consumption than conventional vegetable growing in the garden (Kloas et al., 2015). Furthermore, the water footprint of the inhabitants is reduced because the need for fresh food can partly be covered by self-cultivation. The world-wide average for 1 kg of tomatoes is 214 litres of virtual water (Matzke-Hajek and Vereinigung Deutscher Gewässerschutz, 2011). This consumption can be reduced by local cultivation and the use of recycled waste water.

NexusHaus

The NexusHaus was developed as a contribution to the international competition "Solar Decathlon 2015" by a team of the University of Texas at Austin and the Technical University Munich. It was planned and modified for three locations: Austin/Texas, Irvine/California and Munich/Germany. This paper focuses on the location in Texas. The aim was to create a plus energy house based on three principles according to the Cradle to Cradle® philosophy: Waste equals food, use current solar income and celebrate diversity (Salfner et al., 2017). The sustainable use of water was a key element in the planning process. The building is based on a modular concept, which can be enlarged for households with many people. In this work, the basic variant of the NexusHaus, which consists of two building parts, a day and a night module, with a connecting terrace, is adapted (Fig. 1).

Figure 1. NexusHaus Floor Plan.

Aquaponics

Aquaponics is a technology for food production, which makes use of the symbiosis of natural material cycles. It combines recirculating aquaculture (fish production) with hydroponics (plant cultivation without soil) by nitrification. The excrements of the fish (ammonium and ammonia) must be removed from the water. Like it is shown in Fig. 2 aquaponics converts these substances by means of bacteria into nitrates, which are then used as plant fertilizers. By absorbing the nutrients, the water is filtered and can be returned to the fish (Blidariu and Grozea, 2011).

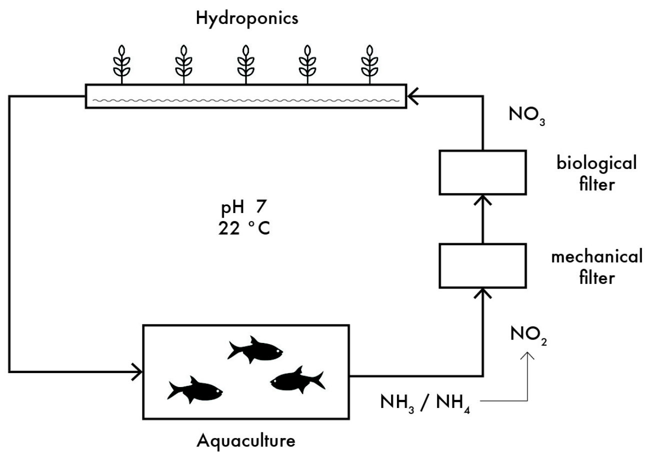


Figure 2. Function of a single circuit aquaponic system.

Aquaponics considerably reduces the water consumption for fish production and plant cultivation. In the research project ASTAF-PRO, 1 kg of fish (tilapia) and 1.67 kg of tomatoes were produced on average with 220.6 litres of fresh water in a testing period of nine months. Compared to a conventional recirculating aquaculture this requires less than ⅓ of the water consumption (Kloas et al., 2015). ASTAF-PRO employed a special technique in which the aquaculture and hydroponics circuits were decoupled and the water quality was regulated separately for plants and fish. (Fig. 3). As a result, both systems could be optimized to meet their needs in particular with respect to the pH value.

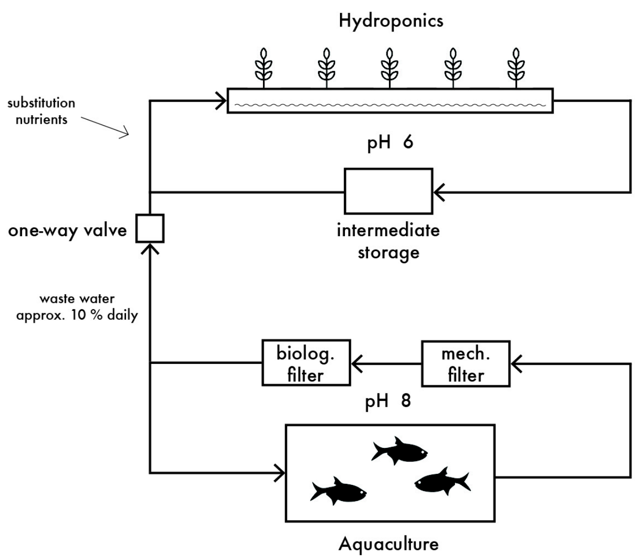


Figure 3. Function of a decoupled aquaponic system.

Since aquaponics works independently of soil conditions and can be adapted to many climatic conditions, it plays an increasing role in the question of food security and food production in water-poor areas. In 2012 the Food and Agriculture Organization of the United Nations (FAO) supported 15 families in the Gaza Strip with small aquaponics units to enable them to produce food independently in backyards and on rooftops (Somerville and Ferrand, 2013). A third project, which is referred to is the aquaponics facility of the “Arche Noah” in Menden, Germany. It is a medium-sized project that has been designed to be particularly energy-efficient in middle latitudes. The three systems are compared in Table 1.

Materials and Methods

To determine the integration of an aquaponic system into a single-family home, several aquaponic systems were first analysed and tested for compatibility (Table 1). The projects showed marked differences in their objectives. The ASTAF-PRO project at the IGB Berlin (also known as "tomato fish") is, for example, a research project that focuses on a larger scale for industrial production. Therefore, a profitable workflow is an important goal.

Table 1. Comparison of listed aquaponic systems

Name and location of aquaponics	Type of system	Size of the fish tank / growing area	Hydroponic system	Type of fish	Type of plants
ASTAF-PRO, Berlin	Decoupled	10 m³/ 116 tomato plants	NFT (nutrient film technique)	Tilapia	Tomatoes
FAO, Gaza	Single circuit	1 m³/ 4 m²	Media based (volcanic gravel)	Tilapia	Mixed
Arche Noah, Menden	Single circuit	2 m³/ 2 m²	Media based (gravel)	Tilapia/ carp	Mixed

The FAO project focuses on autonomous food supply in politically troubled areas. Although a small scale is foreseen, the aquaponic system has been designed for other climatic conditions and is, therefore, only to a limited extent comparable to the NexusHaus. Also, the aquaponic project of the “Arche Noah” in Menden has a small scale. However, the focus is on teaching children in context of environmental education. Another goal is sustainability and energy-efficient operation.

Based on an analysis of the presented systems, key parameters for an aquaponic system, which can be integrated into the NexusHaus, have been defined: Use of recycled water as resource so that no additional consumption of fresh water from the public utility network is needed. Energy-efficient operation throughout the year and a user-friendly handling and care, that doesn’t require expert knowledge.

Water

The aquaponic system is to be supplied exclusively with water, which is produced in the house as a "waste product". The first consideration was to use the condensation of the fan coils. To determine the suitability of this option, the water quantity must first be determined. It is known that when cooling, the interior air forms condensation water because warmer air can absorb more moisture than cold air. For this reason, air conditioning systems have a line to the sewage system of the building. However, the respective amount of condensed water is dependent on numerous components like absolute humidity, relative humidity and air temperatures. In case of the fan coils, only the interior air is cooled and there is no fresh air supply (Daniels, 1996). For this reason, the accumulating humidity only results from the perspiration of the bodies of the inhabitants and their activities in the house.

It is assumed that a person exhales an average of 50 - 150 g of water per hour depending on their activity. In addition, moisture is released to the air when showering, cooking and drying. Therefore, according to a rough estimate it is assumed that three litres of moisture are released to the interior air per inhabitant daily (Baunetz Wissen, 2017). This value, however, fluctuates strongly and is in a great extent dependent on the presence of the inhabitants.

The quality of the condensed water is suitable for aquaponics. The pH is in the neutral range, which corresponds to the requirements. In addition, the pH in the system must be checked and adjusted again and again, to not harm the fish. Although the condensed water of the fan coils can be used in aquaponics, this option is not recommended. The reasons for this are mainly the high effort compared to a very strongly fluctuating and rather low gain. Since the required amount of condensation water cannot be guaranteed with certainty, but an aquaponic system needs fresh water every day, two other options for water extraction from existing resources (rainwater and greywater) will be examined in more detail below.

For the NexusHaus it is planned to catch the rainwater. However, the water thus obtained is intended for the thermal storage tank and is therefore not available for aquaponics (Salfner et al., 2017). In principle, rainwater is very suitable for aquaponics. The EU-funded research project INAPRO, developed based on ASTAF-PRO, aims to cover the fresh water demand completely through the collection of rainwater (Kloas et al., 2015).

The third possibility is the use of greywater. In the NexusHaus the domestic separation of blackwater and greywater is planned. Greywater is waste water from the shower, the bathroom sink and the washing machine that is free from faeces. On average about 163 litres can be collected daily, which are not directed into the public sewage system, but are treated directly in the house for reuse (Salfner et al., 2017). If the demand for toilet flushing and washing machine are removed, a daily average of 120 litres remains, which could be utilised to the aquaponics. In this case as well, the water quality must be monitored and adjusted if necessary.

An aquaponic facility needs about 10% of the water volume of fresh water every day. This value can be reduced even further with well-balanced and monitored system. ASTAF-PRO provides, for example, 3-5% water requirement per day (Kloas et al., 2015). When using recycled greywater, the required amount of water would be reliably available and it would also be possible to tide over several days if the inhabitants were not present.

Location

For an integration of aquaponics into the NexusHaus, it must be decided where the system is to be placed on the site. Various possibilities are conceivable. A placement within the thermal envelope has the advantage of constant temperatures. Nevertheless, this option is discarded because the humidity should be higher for plant cultivation than it is in most dwellings and fish odours of aquaculture could disturb the well-being of the inhabitants. In addition, there is a greater need for artificial lighting to ensure good plant growth and the housing space of the NexusHaus has been narrowly dimensioned.

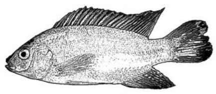
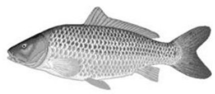
An open-air planting is also feasible. In this case, however, control of the temperatures becomes more difficult. In addition, the rain shelter of a greenhouse counteracts a pest infestation (tomato late blight) (Meyer-Rebentisch, 2017).

After weighing up these aspects, the decision was made to stay on the south side of the day module, as originally planned in the NexusHaus (Fig. 1). In contrast to the competition design, the system is placed in a greenhouse, which also houses the fish tank. In the combined placement of fish and plants, a favourable metabolism takes place. The plants convert the CO_2 released by the fish into oxygen (Kloas et al., 2015). The area between the ramp and the house wall offers enough space for a small aquaponic unit on an area of about 6 m².

Fish

The selection of suitable fish for aquaculture should be made regarding regional conditions. The corresponding comparison factors of three fish species are listed in Table 2. Tilapia are particularly suitable due to their uncomplicated housing conditions and have proved themselves as "standard fish" for aquaponics. However, other species are also possible. In Central Europe, where temperatures are lower than in Texas, carp and trout would be an option. The carp, because it is very resistant even at cold temperatures. The trout, because it is a very popular food fish. Trout is excluded because it gets along very badly with water temperatures above 20 ° C (Würtz, 2017). According to the food preferences in the US, the African catfish is considered as an option for the location in Austin/Texas.

Table 2. Different fish species for aquaponics


	Nile tilapia *(Orechromis niloticus)*	Common carp *(Cyprinus carpio)*	African catfish *(Clarias gariepinus)*
Temperatures	14-36 °C (optimal 27-30 °C)	4-34 °C (optimal 25-30 °C)	5-34 °C (optimal 24-30 °C)
Stocking density	60-150 kg/m³	10 kg/m³	max. 350 kg/m³
Oxygen content	With oxygen supply higher feed conversion ratio	No supply necessary	Tolerates little oxygen
Consumption	Versatile food fish	Many bones, very fat, only moderately popular	Versatile, very popular in America

For the NexusHaus tilapia are selected as suitable aquaculture fish. Due to the low demands regarding the housing conditions, their tolerance to high water temperatures, which are to be expected in the summer and the proven suitability for aquaponics, they are most likely to be used for year-round operation. If favoured by the inhabitants, carp or catfish can be used as an alternative. For these two species, there is less quantified experience in aquaponics, though.

Plants

For the inhabitants of the NexusHaus, the handling and the use are particularly important in the selection of the plants. For this reason, a "media-based bed" should be chosen, in which different plants can be cultivated. The substrate used are coconut fiber mats, which must be exchanged more frequently than mineral substrates, but are compostable in the sense of Cradle to Cradle® (Somerville et al., 2014). It would be ideal to find a regionally available organic raw material, which can serve as a substrate.

For the planting mainly tomatoes are used, as well as herbs and lettuce. With these plants, the design and calculation of the aquaponic system is made. However, plants can be replaced at pleasure (for example, cucumber and pepper instead of some tomato plants).

Results

In order to achieve higher yields and improve the stability of the system, the decision was based on a two-circuit system. The first circuit contains a recirculating aquaculture with tilapia and is connected via a one-way valve to the second circuit, which contains hydroponics. The entire system is housed in a greenhouse that can be shaded and additionally has air conditioning to compensate for the high temperatures that prevail during the summer months in Texas.

The fish tank holds a volume of 500 liters. It contains 35 kg of fish which is graded in different sizes. Large fish are regularly removed and smaller ones are added so that the stocking density is always in the ideal range of 60-150 kg / m³. Figure 4 shows the arrangement of the aquaponic elements. Above the fish tanks are the beds located. The waste water from the fish tank is cleaned from solids in the mechanical filter and nitrated in the biological filter. The water then flows through the one-way valve into the sump, where missing nutrients are added and pH is adjusted. The water is pumped to the beds where strong starters like tomatoes, peppers and cucumbers are grown. Lettuce and herbs can always be added in the beds because they are less nutrient-needy.

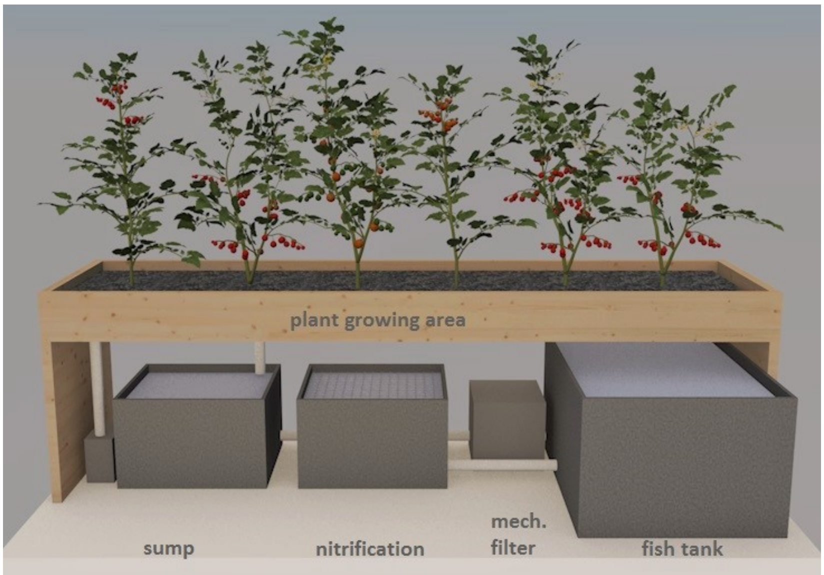


Figure 4. Design of the NexusHaus aquaponic unit.

The fish tank is insulated to compensate for large temperature fluctuations. In winter, night temperatures in Texas can approach the freezing point, which is why a heat exchanger is installed for heating and cooling. It is connected to the thermal storage of the house. The presented aquaponic produces about 75 kg fish per year and 50 kg of tomatoes or other vegetables in a growing season of eight months.

Discussion

When integrating an aquaponic system into a single-family house, it must be clarified whether the system can still be assessed as "sustainable". It is remarkable that a high energy expenditure is necessary in order to keep all parameters in equilibrium. For example, heating energy must be applied in winter and cooling energy in summer. In addition, investment costs are relatively high for a small plant. In the case of a larger installation, these critical points are significantly reduced. However, if it is possible to cover the energy expenditure from self-generated renewable energies and the investment costs are taken into account, the question arises as to how the system is pleasant to use for its users. Basically, aquaponics is only to be used after thorough instruction. A good understanding of fish farming and plant rearing is important to avoid mistakes. The system requires a lot of maintenance. Despite feeding equipment and automated operation, a daily inspection is urgently recommended. The quality of water must be checked regularly, which in the ideal case could be transmitted via sondes that send digital readings to the residents' smartphone.

The presented results could not be practically tested. This would be necessary, in particular, to determine the climatic conditions in the small greenhouse more precisely, thereby quantifying the energy expenditure.

Conclusions

It is possible to integrate an aquaponic system into the NexusHaus and to reuse water that is generated as a waste product. The fresh water supply with treated greywater is favored because the required amount is constantly available. The system is to be housed in a greenhouse on the south side of the day module. It contains a 500 litre tank, which is used to cultivate tilapia with 35 kg biomass all year round. The hydroponic plant cultivation is to take place from April to October in a media-based grow bed in which coconut fiber matts serve as substrate. A heat pump to the thermal storage of the NexusHaus keeps the temperature in the fish tank constant. The yields of 75 kg of fish and 50 kg of tomatoes per year would lower the needs of the residents for external food supplies and thus have a positive impact on the water footprint.

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