AQUAPONICS: A SUSTAINABLE FOOD PRODUCTION SYSTEM THAT PROVIDES RESEARCH PROJECTS FOR UNDERGRADUATE ENGINEERING STUDENTS

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ABSTRACT

Aquaponics is a closed-loop, recirculating fresh water system in which plants and fish grow together symbiotically. Aquaponics resembles a natural river or lake basin in which fish waste serves as nutrients for the plants, which in turn clean the water for the fish. Tilapia and salad greens or herbs are common fish and plants grown in an aquaponics system. The external inputs to an aquaponics system are fish food, a minimal volume of replacement water, and energy for lighting and heating the water. Aquaponics is particularly suited to arid climates because it uses much less water to grow plants than soil-based systems. In fact, the only water that is lost from an aquaponics systems is by evaporation and transpiration from the plants.

The relationship between the amount of external energy (fish food plus energy for light and heat) to the output (weight of fish and plants) has not been well quantified for aquaponics units in temperate climates. The need to quantify the relationship between inputs-outputs presents opportunities for research projects for undergraduate engineering students in mechanical, electrical, and civil and environmental Engineering. The following are examples:

Sensors: What types of sensors are ideal to measure air and water temperature, water pH, dissolved O_2, and nitrogen species?
Thermodynamics: What type of water heating system is most efficient for maintaining desirable water and air temperature?
Water Quality: What are the optimal methods to filter out the solid fish waste (feces), maintain a biologically active filter environment, and control nutrients in the system to enable healthy growth of fish and plants?
Hydraulics: What size of pump is needed to maintain optimal flow rate?
System Design: What are the optimal ratios between fish tank volume and growth area volume? What is the optimal drop in water level between components to utilize a gravity-based system?

The Marquette University College of Engineering is building a laboratory to conduct aquaponics research. Lessons learned from this research will aid the development of aquaponics in temperate climates but also possibly in tropical regions.

KEYWORDS
Aquaponics, recirculating water system, tilapia

RESUMEN

Acuaponía es un sistema artificial con agua redistribuido para cultivar los peces y las plantas para consumo por humanos. Acuaponía imita la naturaleza, como la costa de un lago, en que los peces y las plantas viven juntos con las ventajas mutuas. Específicamente, el desperdicio biológico (amoníaco) se hace la comida para las plantas y las plantas limpian el agua para los peces. Las ventajas de acuaponía incluyen que requiere ningún tierra para cultivar verduras, minimiza el consumo del agua dulce, y puede ser ubicado en cualquier sitio (siempre y cuando hay un fuente externo de energía).

El análisis de entrada-salida de acuaponía no ha sido cuantificado bien para el clima templado, por ejemplo la región de los Great Lakes en EEUU. El costo de los peces y las verduras crecidos por acuaponía en la región de los Great Lakes no es conocido. La necesidad para cuantificar la relación entre entrada-salida presenta las oportunidades para proyectos de investigación por los alumnos bachilleratos de los departamentos de ingeniería mecánica, eléctrica, y civil y medioambiental. Ejemplos son a continuación:

Sensores: ¿Cuáles tipos de sensores son apropiados para medir la temperatura de agua y aire, PH de agua, y oxígeno y nitrógeno biológico en el agua?
Termodinámicas: ¿Cual tipo de sistema para calentar el agua es más eficiente para mantener la temperatura querido en el agua y aire?
La Calidad del Agua: ¿Cuáles son los métodos más óptimos para filtrar los excrementos de los peces, mantener un ambiente de filtro biológico, y controlar los alimentos en el sistema?
El Diseño de Sistema: Cuanto es el ratio óptimo entre el volumen del tanque para los peces y el área para el crecimiento de las plantas?

El Colegio de Ingeniería de la Universidad de Marquette está construyendo un laboratorio para hacer la investigación de acuaponía. Las lecciones de esta investigación ayuden el desarrollo de acuaponia en los climas templados además los climas tropicales. Si a una universidad latina le interese este proyecto, por favor contacte al autor principal.

PALABRAS CLAVES

Acuaponía, sistema redistribuido del agua, tilapia

1. BACKGROUND

The term “aquaponics” is derived from the “aqua” in aquaculture and “ponics” in hydroponics. Aquaculture is fish farming, where fish are grown in a controlled environment. A disadvantage of aquaculture is that the water must be treated to control ammonia, which is released in fish waste, in order for the fish to survive. In hydroponics, plants grow in water, but nutrients must be added to the water in order to feed the plants. Aquaponics uses the fish waste in aquaculture (nutrients such as nitrogen-containing ammonia) as the food for plants grown in water (hydroponics). This process is the same as that occurring in nature, such as in a river or lake basin, where plants and fish live together. Aquaponics is the closed-loop recirculating water system that mimics the natural process in rivers and lakes.

Compared to soil-based systems, aquaponics offers a more sustainable method to grow vegetative food for human consumption in that it uses much less water. The only water that is lost is due to evaporation and transpiration from the plants. Salad greens and tilapia or perch are typical plants and fish grown in aquaponics systems.

Although the field of aquaponics is growing world-wide, the capital and operational costs of producing the plants and fish have not been quantified intensively in the peer-reviewed literature. Goodman (2011) reported that literature about the financial feasibility of aquaponics is scant. The relationship between the amount of external energy (electricity for light, energy for heat, and fish food) to the output (weight of fish and plants) has not been directly measured for aquaponics units in the Great Lakes region of the US, which has a temperate climate. For example, a US consumer can buy one kg of frozen tilapia grown in a fish farm in Indonesia at Costco for approximately $17.6 / kg; however it is difficult to compare the cost of the Indonesian-grown tilapia to the cost of tilapia grown at two local recognized leaders of aquaponics in Milwaukee, Growing Power and Sweet Water Foundation, because the total costs (start-up and operational) have not been quantified. The lack of quantification of the total inputs (capital, energy, fish food, and labor) has suppressed aquaponics progress for small businesses and homeowners because it is difficult to compare the total costs of local aquaponics systems to salad greens and fish grown in remote locations such as California, Florida, or offshore.

2. LITERATURE REVIEW

The earliest integrated system for fish and vegetables appears to have been documented in the 1980s. The first article, published by Watten and Busch (1984) described aquaponics as a recirculating water system for plants and fish. This work was performed at the University of Virgin Islands (UVI). James Rakocy, a prolific author of aquaponics research (Rakocy, *et al.* 2006; Rakocy, 2012), continued the work at UVI and developed the deep-water aquaponics system (also called floating raft system). Also during the 1980s, aquaponics was being developed by the New Alchemy Institute and reported by Zweig (1986). During the latter part of the 1980s, Mark McMurty at North Carolina State University developed the Integrated Aqua-Vegiculture System (IAVS) (McMurtry, *et al*., 1990; McMurtry, 1992), in which water flows through a hydroponic bed of growing media such as gravel or sand. The deep-water and IAVS are the two dominant systems for modern aquaponics.

In 2006 Rakocy et al. reported production and sales data for different crops from a UVI aquaponics system at the Crop Diversification Center South in Alberta, Canada. These data did not include the capital, operating, and marketing costs, which are considerable according to Rakocy. Addressing these extra costs, Goodman (2011) conducted a study of small- and medium-scale aquaponics systems (750 gal and two-3750 gal systems) at Growing Power in Milwaukee to determine if any of their systems were profitable. She found that three out of the four aquaponics systems analyzed were not profitable based on fish and vegetable sales alone. However, changes to the business model may make the systems profitable. For example, adding an aquaponics unit to an existing business (such as a restaurant) would eliminate incorporation costs, some capital costs (land and equipment), and would use downtime of existing employees. In Goodman's (2011) study, she included capital and operational costs (electricity, heat, fish food, and labor), which were estimated by owners and operators at Growing Power and also outside sources. She did not measure the exact amount of operational inputs over time, which is a limitation of her study and exposes a major research void that is prevalent in the aquaponics literature. *Inaccurate estimates of operational inputs can determine to a large extent whether an aquaponics system breaks even or is profitable.*

The uncertainty about the economic feasibility of an aquaponics system presents opportunities for undergraduate engineering students to explore how the design of components of an aquaponics system affects the overall efficiency and feasibility. These projects have a scope that are within the capabilities of undergraduate engineering students and would fit within the structure of a one- or two-semester course.

3. DESIGN OF A SMALL AQUAPONICS UNIT

The authors formed the Marquette University (MU) aquaponics team in 2012 to start a research program that addresses the primary research void of aquaponics for temperate climates, namely its economic feasibility. The MU team decided to focus on a small aquaponics unit (approximately 1.6 x 3.2 m) rather than a large commercial unit for the following reasons:

- A small unit would cost less than a commercial unit, and thus may be within the budget of homeowners, small businesses, and researchers.
- A small unit would be easier to control in an experimental study.
- A small unit can fit in one bay of an automobile garage and could be operated by homeowners.
- A small unit could be housed in the unused portion of a small business, such as a restaurant.
- Scaling small units upward, i.e. increasing the number of units, appears to be easier than scaling down a large unit that typically has water tanks with capacity of 10,000 L.
- If there were a major problem with multiple small units, such as water or biological contamination, then the source of the problem could be isolated in one or two units without shutting down the entire system. With a commercial system that has large tanks, the entire system would have to be shut down to fix the problem.

A proposed small aquaponics system is presented in this section. This system uses the floating raft method (deep water system) developed at the University of Virgin Islands by James Rokocy and colleagues during the 1980s (Rokocy, *et al.,* 2006). In a floating raft system, the plants sit on a Styrofoam board that floats on water (**Figure 1**). The roots hang down into the water, where the roots absorb the nutrients. This system requires only one pump to pump the water into the fish tank, and then uses gravity for the water to flow through the bio-filter, plants, and sump pump tanks. Air is pumped through tubes into the fish and plants tanks, thereby oxygenating the fish and the biofilm that forms on the tank and the underside of the Styrofoam sheets.

As shown in **Figure 2**, the small aquaponics unit has the following components:

- **Fish tank**, capacity of 1,000 L. Maximum fish density is 0.06 kg/ L (0.5 lbs / gal) or 60 kg of fish per 1,000 L. Tilapia is a popular fish for aquaponics because it grows fast and has a mild flavor.
- **Solids removal and bio-filter tank**. A pre-filter material, such as a sponge, collects the solid fish waste (feces), and bio-filter structures, such as bio-balls, are placed in this tank. The bio-filter structures enable bacterial growth that converts the ammonia species in the waste to nitrites and then nitrates, which is the food for the plants.
- The **plants tank** houses the plants with their roots hanging down into the water.
- In the **sump pump tank,** the water is pumped into the fish tank. Replacement water can be added in this tank to regulate the depth of water in the system.

Figures 3 and **4** show 3-D, cut-away, and cross-sectional views of the system.

The small aquaponics system was designed so that it could be assembled and disassembled easily with only bolts and nuts (no nails or screws). The boards are conventional pine 2x4, 2x6, and 2x8 lumber with a width of 1.5 in. (38 mm) Treated lumber was not considered because of the possibility that the chemical treatment would contact the water. The plants and sump pump tanks are formed by the pine boards. Five cm (2 in.) thick foam boards are placed against the pine boards, and then a food-grade EPDM (ethylene propylene diene monomer) liner is laid on top of the foam boards. The fish tank is a food-grade polyethylene tank. A high efficiency light is mounted above the plants tank to supplement natural light. The plumbing pipe and tubing is food-grade plastic.


Figure 1. In a floating raft system, the body of the plants sits on top of Styrofoam boards that float on water, and the roots hang down into the water (left photo). A large commercial aquaponics unit in a green house is shown in the photo on the right.

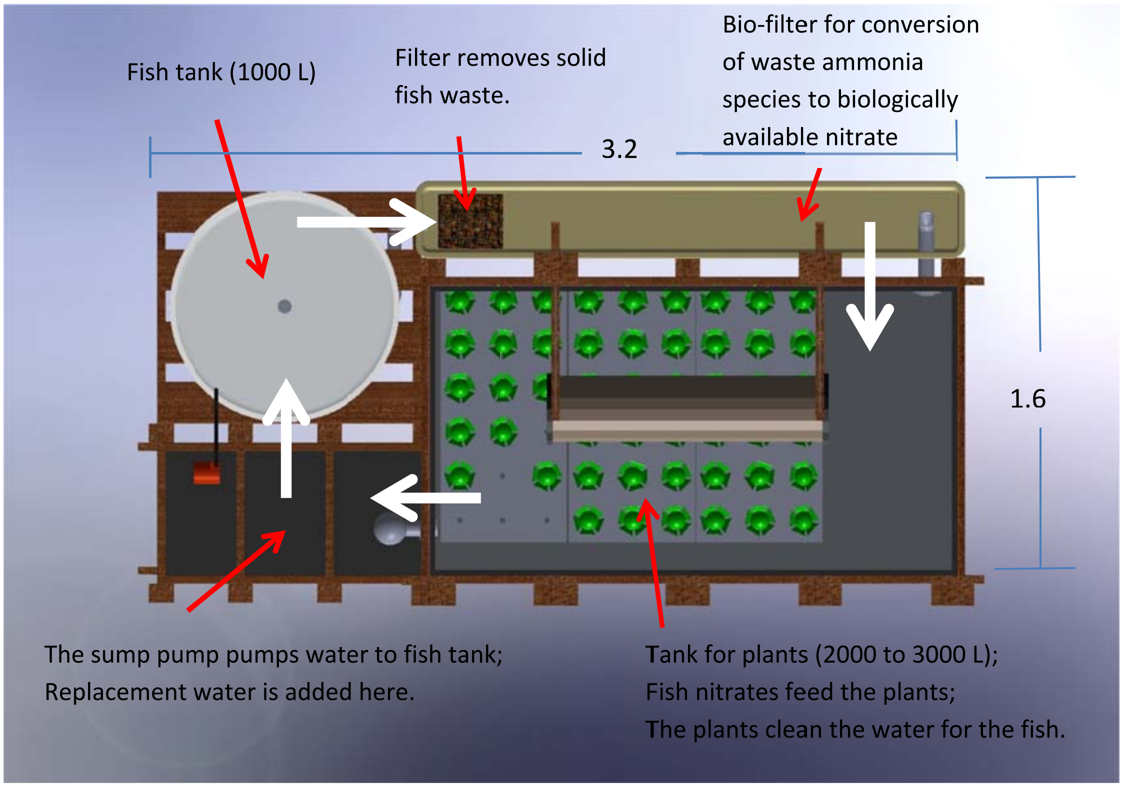

Figure 2. Top view of a small aquaponics system with descriptions of components. The white arrows represent the flow of water.

Figure 3. A 3-D drawing of the small aquaponics system (left). A cut-away view of the water tank for plants (right).

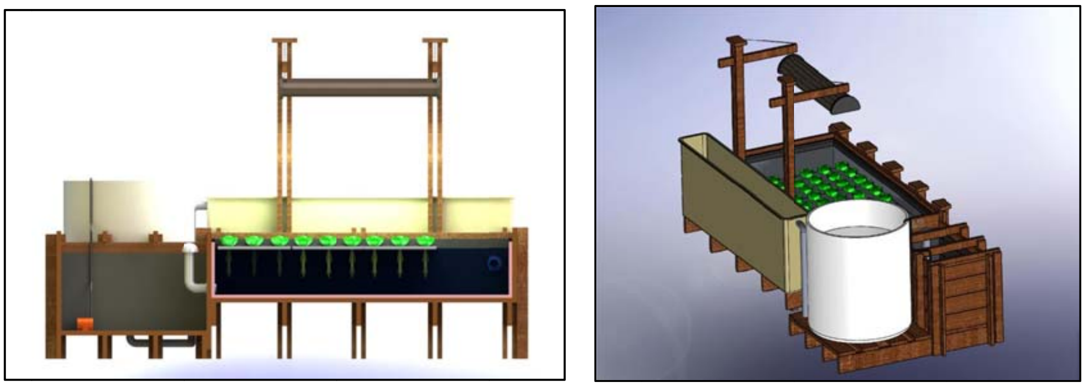

Figure 4. A cross-sectional view of the sump pump and plant tanks (left). A 3-D view from the rear showing the fish tank (cylinder) and the long rectangular tank for solids removal and bio-filter (right).

4. TOPICS FOR UNDERGRADUATE RESEARCH PROJECTS

The inter-disciplinary nature of the aquaponics components and the need to quantify the relationship between inputs-outputs presents opportunities for research projects for undergraduate engineering students in Mechanical, Electrical, and Civil and Environmental Engineering Departments. The following are examples:

Sensors: What types of sensors are ideal for measuring air and water temperature, water pH, dissolved O_2, and nitrogen species?

Thermodynamics: What type of water heating system is most efficient to maintain a desirable water and air temperature? Can the operational measurements (required electricity and heat) from one setting be extrapolated to estimate the operational costs in other climates?

Water Quality: What are the optimal methods to filter out the solid fish waste (feces) and introduce necessary bacteria into the system?

Hydraulics: What size of pump is needed to maintain optimal flow rate? What diameter of pipe will optimize water flow and reduce pump power? What is the best pipe design and connections to move water from one tank to another?

System Design: What are the optimal ratios between fish tank volume and grow area volume? What is the optimal drop in water level between components to utilize the gravity system?

Engineering Economy: What is the rate of return on the system, based on local cost of labor and electricity? Is it profitable? If so, for which markets? (US, Central America, South America)

Data Collection and Monitoring: What type of system is cost-efficient to collect data from the sensors and make the data available for remote monitoring through the internet?

The undergraduate engineering projects could be part of senior capstone courses or other design courses. The scope of each project could be adjusted for a one- or two-semester project.

5. DISCUSSION AND CONCLUSION

A small aquaponics system presents opportunities for undergraduate engineering design and analysis projects. The diverse aspects of aquaponics components can be tailored to specific engineering departments or interdisciplinary teams. There is great opportunity for design in these projects, which may satisfy the design requirements for accreditation. For example, ABET (Accreditation Board for Engineering and Technology) requires design content in Mechanical Engineering curricula, and some courses may use aquaponics for their design projects.

In addition to the benefits to engineering pedagogy, aquaponics is a topic that has broad interest among many young people because of its benefits to more sustainable societies. The millennial generation (born 1982 to 2005), which comprises the current traditional university students, tend to be interested in projects that integrate technical solutions to solve social problems while accounting for economics and the environment. According to Howe and Strauss (2007), the millennial generation favors community building and civic-minded projects, and as such, aquaponics projects would most likely be received positively among millennial students. One societal benefit of aquaponics is that some families would be able to grow their own protein and vegetables, thereby reducing their food costs and possibly increasing their standard of living.

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