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**Determining the Most Efficient Type of Growth Light for an
Aquaponics System using Yellow Lantern Chilies
(*Capsicum chinense*)**

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Abstract

Aquaponics, a type of urban agriculture, shows potential to produce large amounts of food with little water and land requirements. Thus, aquaponics could help address the issue of feeding the growing worldwide population. However, multiple challenges, both technical and economical, are associated with aquaponics, making large-scale implementation of these systems difficult – these systems can require tremendous amounts of energy. This study sought to determine the most efficient types grow lights in aquaponics systems by comparing the growth rates of yellow lantern chilies (*Capsicum chinense*) when grown under four different types of growth lights: light-emitting diode (LED), metal halide, fluorescent, and induction. The study measured the energy usage of each light source to determine which type used the least amount of energy, in an effort to find how to reduce the energy expenses of aquaponics systems, to make the systems more economically feasible. On average, use of LED and induction growth lights resulted in the most overall growth and fastest growth rates of pepper plants. These lights are also known to be relatively energy efficient. Thus, use of LED and induction lamps in aquaponics systems could result in maximum energy efficiency by increasing plant production and reducing energy costs. Consequently, implementation of these lights could make aquaponics more economical for large-scale implementation in the future.

Introduction

Stresses of Population Growth

In the last two centuries, the human population has experienced rapid growth. The current world population is now more than 7 billion people, compared to less than 1 billion only 200 years (Roser 2015). From 1900 to 2000, the human population more than quadrupled from 1.5 billion people to 6.1 billion (Roser 2015). As overall consumption of resources has grown alongside the population, an increasing amount of stress has been placed on the environment in an effort to produce an adequate amount of food and clean water.

Today, some 70% of available freshwater is used for agricultural irrigation; furthermore, worldwide, nearly 70% of planted crops never reach the harvest stage due to environmental factors such as drought, floods, pests, and so on (Despommier 2010). Presently, about 40% of available land is used for agriculture (Fritsche et al, 2015), an amount of land comparable to the size of South America (Despommie, 2010). By the year 2050, the global human population is projected to reach 9.6 billion (Goddek 2015). With traditional farming practices, assuming no increase in their efficiency, approximately 8,500,000km² of additional cropland would be required to support that amount of people (Despommier 2010).

Moreover, about 5.7 billion people currently live under conditions of relative water scarcity, and about 450 million are under severe water stress (Vörösmarty et al. 2000). Vörösmarty et al. (2000) suggested that much of the world may face substantial challenges relating to clean water availability and water-related infrastructure in the future, potentially within the next 25 years. In light of current and projected water

shortages and a lack of available farmland to support the growing population (Despommier 2010), it is appropriate to seek more resource- and water-efficient methods of food production.

Inefficiencies and Environmental Costs of Traditional Agriculture

Developments in agricultural technology have gradually increased food production for thousands of years. Significant developments in the 18th and 19th centuries in particular paved the way for the population explosion of the 1900s (Lambert 2013). However, extensive implementation of conventional agriculture around the world has had a detrimental effect on soil.

Soil plowing, on which traditional agriculture is largely dependent, releases nutrients and increases the decomposition rate of organic matter; thus stimulating crop growth in new fields. However, repeated plowing of fields leads to long-term decreases in water and nutrient storage capacities of soil (Soil Quality 2011). Plowing also decreases topsoil depth and organic matter content over time, largely due to increased erosion of exposed soil. Increased erosion, in addition to losses in nutrient and water content, causes soil productivity to decline over-time, unless carefully managed (Reganold et al. 1987).

Decreased crop yields due to nutrient losses and increased erosion are often masked when farmers bring in additional topsoil from other locations and apply fertilizers (Lal 2001). However, application of fertilizers to farmland degrades the environment in other ways, as evidenced by the Gulf of Mexico “Dead Zone” (Kling 2013; Motsinger 2015). The “Dead Zone” occurs when fertilizers are carried down the Mississippi River and enter into the Gulf of Mexico. Once in the gulf, fertilizers induce algal blooms, which inevitably lead hypoxic conditions as algae die off and consume the oxygen in the water

during decomposition. The hypoxia degrades populations of fish and other marine organisms (Kling 2013; Motsinger 2015).

Additionally, wide-spread application of pesticides is often a characteristic of conventional agriculture. Pesticides, though they have increased agricultural production, can have many deleterious consequences for the environment. Damage to farmland, fisheries and untargeted flora and fauna are a few examples of pesticide-related issues. Pesticides have also been linked to diseases and increased human mortality in some areas (Wilson and Tisdell 2001).

Finally traditional agriculture systems produce a tremendous amount of food waste. In the United States alone, up to 40% of the food produced does not get eaten (NRDC 2012). Food waste is not an issue in the U.S. alone It is an inefficiency that is common with traditional agriculture around the world (Table 1). Wasting food means that a substantial amount of water, soil nutrients and organic matter has been used to no avail. Food losses occur at various levels of the food production system, including during the farming process, during harvest and packaging, during processing, and during food distribution. The difficulty of maintaining crops throughout every step of the production system is a driving factor for food waste in traditional agricultural systems. Additionally, the fact that traditional farms are often located far from processors and consumers means that transportation costs are high: 10% of the total U.S. energy budget is used getting food to consumers (NRDC 2012).

Table 1. Post-harvest loss estimates for fresh fruit and vegetables (from Parfitt et al. 2010).

Country	Commodities	Post-Harvest Losses (%)	References
Egypt	all fruits	20	Blond (1984) Guerra <i>et al.</i> (1998) Rolle (2006)
	all vegetables	30	
	grape	28	
	potato	18	
	tomato	43	
Venezuela	broccoli	49	
	cauliflower	33	
	celery	48	
	leek	20	
	lettuce	35	
	all FFVs		
India		40	
Indonesia		20–50	
Iran		>35	
Korea		20–50	
Philippines		27–42	
Sri Lanka		16–41	
Thailand		17–35	
Vietnam		20–25	
loss estimates: less developed countries (research prior to 1981)			
	carrots	44	National Academy of Sciences report (1978) and cited in FAO (1981)
	potatoes	5–40	
	sweet potatoes	35–95	
	yams	10–60	
	cassava	10–25	
	onions	16–35	
	plantain	35–100	
	cabbage	37	
	cauliflower	49	
	lettuce	62	
	banana	20–80	
	papaya	40–100	
	avocado	43	
	peaches, apricots and nectarines	28	
	citrus	20–95	
	apples	14	
loss estimates: US and UK			
USA	all FFVs	2–23, farm-retail stage	Kader (2005)
UK	all FFVs	approx. 10, farm-retail stage	Garnett (2006)
	‘out-graded’ FFVs	25–40, rejected by supermarkets	Stuart (2009)

Efficiency of Aquaponics

Due to the substantial amounts of waste produced by traditional agriculture, new and more efficient alternatives to food production are needed. Aquaponic-based agriculture is a potential solution. Aquaponics systems combine circulating aquaculture with a hydroponic system to produce both fish and plants for human consumption (Rakocy et al. 2006; Oliver 2015). Ammonia in fish waste is converted by microbes to usable nitrate, which is then absorbed by plants – nitrate is an essential nutrient for plant growth. Due to the easily accessible dissolved nutrients, plants in aquaponics systems can grow rapidly (Rakocy et al. 2006). After the nitrate-rich water moves through the plant tanks, it can then be reused again by the fish, creating a continuous cycle of water movement between fish and plants, allowing for growth of both, while reducing water loss (Rakocy et al. 2006).

In traditional agricultural systems, only about 10% of water gets absorbed by plants, whereas about 90% is lost to runoff or evaporation (Blidariu and Grozea 2011). Recirculating aquaponic systems, however, have been shown to be much more water efficient, typically losing less than 10% of water volume per day (Blidariu and Grozea 2011). Goddek et al. (2015) showed that recirculating aquaponics systems can be even more efficient, reusing 95%-99% of water. Due to the fast-growing nature and high levels of water conservation, aquaponics systems have the potential to grow more food on less and lower quality land with less maintenance than traditional agriculture (Rakocy et al. 2003; Oliver 2015). For example, Rakocy et al. (2003) showed that aquaponically produced basil grew three times faster and required less maintenance than field grown basil.

Additionally, because aquaponics systems are typically managed indoors, under controlled conditions, crops and fish can be harvested from these systems year-round. Since aquaponics systems are not exposed to seasonal changes and harsh weather, they can be much more annually productive, per unit area, than traditional farmland. Moreover, because of the ability to produce these systems indoors, aquaponics systems can be located within cities, where food demand is highest. As a result, wide-spread application of these systems would mean that food is located much closer to consumers. Thus, shorter transportation distances between producers and consumers could radically reduce the above mentioned energy use and food waste produced in conventional agriculture (NRDC 2012).

Pitfalls of Aquaponics

Despite the efficiency and potential of aquaponics, these systems have challenges that hinder large scale implementation. Aquaponics systems rely on a delicate balance between three types of organisms: fish, plants and bacteria (which turn fish waste into usable nutrients). Conditions within the systems must be supportive of all three types of organisms for the system to function optimally (Goddek et al 2015; Shafeena 2016; Tyson et al 2011; Somerville et al. 2014). (Water quality conditions ideal for each organism and for the system as a whole are shown in Tables 2.1 and 2.2.) Therefore, water quality testing is important in these systems in order to ensure optimal production. Treatments – such as the additional of bases, micronutrients, or changing fish-feeding patterns – may also be necessary to keep conditions ideal.

Table 2.1. General water quality tolerances for fish (warm- or cold-water), hydroponic plants, and nitrifying bacteria (from Somerville et al. 2014).

Organism type	Temp (°C)	pH	Ammonia (mg/litre)	Nitrite (mg/litre)	Nitrate (mg/litre)	DO (mg/litre)
Warm water fish	22–32	6–8.5	< 3	< 1	< 400	4–6
Cold water fish	10–18	6–8.5	< 1	< 0.1	< 400	6–8
Plants	16–30	5.5–7.5	< 30	< 1	-	> 3
Bacteria	14–34	6–8.5	< 3	< 1	-	4–8

Table 2.2. Ideal parameters for aquaponics as a compromise between all three organisms (from Somerville et al. 2014).

	Temp (°C)	pH	Ammonia (mg/litre)	Nitrite (mg/litre)	Nitrate (mg/litre)	DO (mg/litre)
Aquaponics	18–30	6–7	< 1	< 1	5–150	> 5

A second challenge to aquaponics systems is pest and disease control. Various types of fish and plants are grown in aquaponics systems. Subsequently, aquaponics can be prone to multiple types of disease and pest infestation. However, since the systems rely on a delicate balance of organisms to function optimally, typical pest and disease treatments cannot be used in these systems (Goddek et al 2015). For example, antibiotics could not be used to treat a fish disease, because they would kill the essential nitrifying bacteria in the aquaponics system. Pesticides for plant pests also could not be applied because they could be detrimental to the fish. Consequently, dealing with pests and disease in aquaponics systems can be a delicate process. Methods such as reducing crop and fish density can help reduce the likelihood that pests or disease would spread through the system. Using mutualistic microorganisms as a method of pest bio-control is also a potential solution. Nevertheless, currently disease and pest regulation in these systems can be difficult and more research is needed to determine the most effective control methods (Goddek et al. 2015).

One final major challenge to aquaponics systems is high-energy costs. In aquaponics systems, fluctuations in temperature and light availability can harm fish, plants, and bacteria in the system or cause system productivity to decrease; consequently, maintaining stable conditions is crucial (Goddek 2015). Sustaining temperature and light availability, however, can require a lot of energy, making maintenance of the conditions an expensive proposition.

The Purpose of this Study

In order to maximize the potential of aquaponics agricultural systems, it is important to optimize the efficiency of the systems on an economic basis. If these systems cannot be made efficient enough to be economically feasible, then they will not be implemented on a scale large enough to benefit the environment or increase food security. Because one of the biggest hindrances to aquaponics systems is the cost of energy, discovering the most efficient type of growth lights could be very beneficial to the long-term implementation of aquaponics systems. The aim of this experiment was to find what type of growth light produces the highest plant growth rate with the lowest energy usage.

Different types of lights use varying amounts of energy – whichever light uses the least energy will be the least expensive to operate. However, for application in agriculture, it is also important to take into account what growth rates different lights may produce in the plants. Simply knowing what light uses the least amount of energy is not enough. To make aquaponics more efficient, it is important to know what types of lights produce the most plant growth, for the least amount of energy.

In this experiment, yellow lantern chilies (*Capsicum chinense*) were grown in four controlled aquaponics systems at Kentucky State University. Each system was divided

further into four sections, and each section was grown under a different type of grow light: induction (IND), metal halide (MH), fluorescent (FL), or light emitting diode (LED). Induction lights use an electric or magnetic field to generate power, which is then transferred into a gas discharge lamp, which emits photons. Metal halide lights produce light by creating an electric arc in a gaseous metal-halide mixture. Fluorescent lights run an electric current through mercury vapor, producing ultraviolet light. LED lights contain a semiconductor. When a sufficient amount of voltage is passed through the semiconductor, energy is released as photons.

Plants were grown for 55 days under the various light sources. Overall growth, growth rates and average electricity usage for each type of light were determined. This study had two purposes: (1) to determine which type of light produces the most plant growth and (2) to determine which light sources could be used to reduce energy costs, making operation of aquaponics systems more economically feasible.

Since the different types of lights have different properties and may produce light on varying spectrums, they may not all influence plant growth the same way. This experiment seeks to determine what type of light produces the most plant growth with the least amount of energy. In other words, which light produces the most product for the least cost? By determining which light produces the most plant growth per unit of energy, this experiment can help aquaponics users optimize their systems. Such optimization could make aquaponics more economically feasible, resulting in the implementation of aquaponics on a larger scale. Large scale implementation of aquaponics could not only increase food production and food security, but could reduce reliance on traditional

agriculture, thus alleviating some of the issues with traditional agriculture, such as fertilizer and pesticide pollution, soil degradation, and inefficient water use.

Materials and Methods

System Design

The experimental design consisted of four aquaponic systems, each of which contained a total of six water tanks: a 110 gallon fish tank, a 55 gallon clarifier tank for filtering out large solids, a 45 gallon biofilter, two 120 gallon plant tanks, and a small sump tank.

Water began in the fish tank, where the fish were raised and fed, and thus where fish waste (the nutrient source for the plants) was produced (Figure 1). From the fish tank, water flowed into a solid-filtering tank. This tank was divided in half by a plastic barrier, which reached to the top of the tank but left room for water to pass underneath. Consequently, water descended to the bottom of the tank before filling the other side and passing on to the biofilter. The descent of the water provided ample time for large solid waste to settle out into the bottom of the tank, where it was then be flushed out on a daily basis using a release valve at the bottom of the tank. Water entered the biofilter (another water tank filled with plastic netting) at the bottom of the tank and flowed up. While the water ascended through the biofilter, fine solids collected on the netting, thus reducing the collection of fine solids on plant roots. If too many fine solids collected on the plant roots, they would interfere with the plants' ability to absorb water and nutrients.

Furthermore, the biofilter allowed for the growth of microbes, which breakdown ammonia-based fish waste, converting it into dissolved nitrate that the plants can use. After passing through the filtering stages, the nutrient rich water flowed into the plant

tanks. The plants were positioned in Styrofoam holders, which allowed the roots hang suspended in the water, while the rest of the plant was supported above. After passing through the plant tanks, water flowed in the sump tank, where water was collected and actively pumped back up into the fish tank to repeat the cycle. The sump pump was the only active pump in the system; the rest of the tank transitions were gravity-fed.

The systems were further divided into four sections, one section for each type of growth light (Figure 1). The order of the lights was different in each of the four systems to prevent any bias that could result from the order in which plants received water. For example, in system one, section one, two, three, and four could have induction, metal halide, fluorescent, and LED lights, respectively. The order of lights per section in system two however would have been metal halide, fluorescent, LED, and induction. Thus the order of lights in each system varied and each light appeared in each section once. This was done because plants at the front of the tanks (section one) had access to higher concentrations of nutrients, while plants towards the tank exit (section four) had access to fewer nutrients due to continual absorption as water moved through the tank. Alternating the order of lights in each system reduced the potential that differences in plant growth were affected by nutrient availability and thus enabled conclusions on plant growth to be based on the light sources alone.

Each section of the system was separated using black plastic barriers to prevent light from one section spilling over into adjacent sections and influencing the light absorption by plants in the other sections. Each section contained five plants. One plant was placed in each of the four corners of the section, with one plant in the middle,

Light intensity readings for each section were taken at the level of the highest leaves from each section's tallest plants. These measurements were taken twice per week using a Photosynthetically Active Radiation (PAR) meter. PAR meters measure the intensity of light within light spectrum that plants primarily use for photosynthesis. PAR was measured to make sure that the plants under every light were receiving the same amount of light, ensuring that some plants would not have advantages over others due to more light intensity. Light heights were adjusted twice per week in order to maintain a PAR reading of $200 \pm 5 \text{ umol/m}^2/\text{s}$ over each section.

Water Quality Assessments

Water pH was measured twice daily and maintained using additions of potassium hydroxide (KOH) and calcium hydroxide (CaOH) into the sump tank when the water became too acidic. Under normal conditions, water in aquaponics systems tends to become acidic due to the buildup of nitrogen waste. Therefore, the aforementioned bases were mixed gradually into the sump tank of each system to keep the system's water within a pH range of 6.8-7.0. Base additions were added in increments of 15g-30g at a time, depending on the pH of the water at that time.

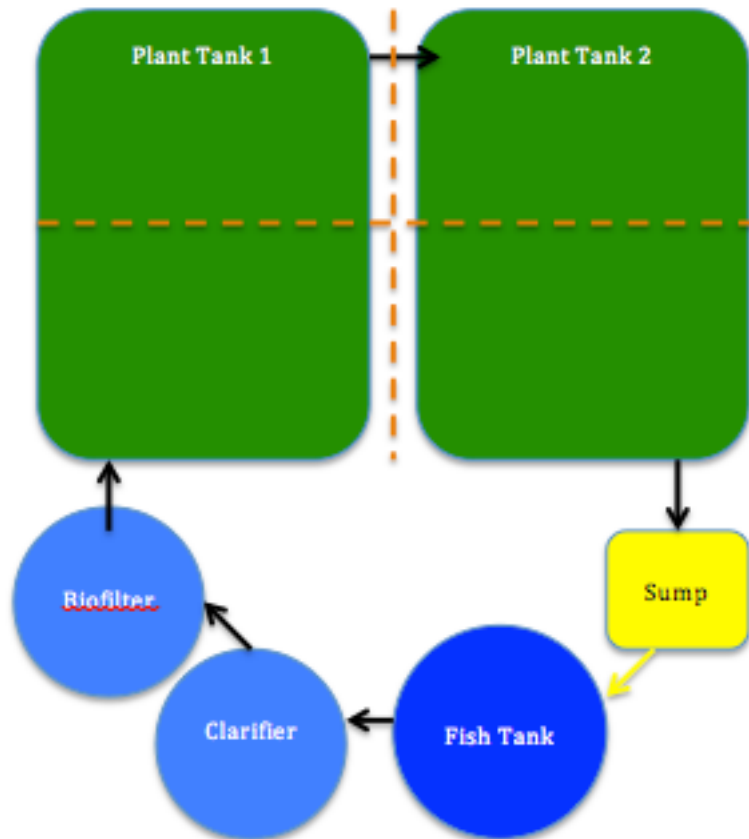


Figure 1. The diagram shows the layout of each of the four aquaponic systems. The arrows demonstrate the continuous flow of water through the six tanks used in this system. Each tank is represented by a color. Dark blue denotes where the fish were kept and where waste (nutrients) originated. Light blue indicates tanks that were important for water cleaning processes. Green tanks are where plants were grown in float beds in nutrient-rich water. Yellow denotes where used water collected before being actively pumped back into the system. Arrows indicate the direction of water flow between tanks. The yellow arrow denotes water that is actively pumped, whereas black arrows are gravity-fed. The dotted orange lines indicate the location of plastic walls used as light barriers, effectively isolating each section of the fish tank from the other sections, thus allowing a different light source to be used within each section. Plastic barriers also encircled the two fish tanks as a whole, although not shown in the diagram, to reduce the amount of ambient light reaching the plants from outside the system.

Furthermore, detailed water analysis tests were conducted twice weekly. Nitrite, nitrate, total ammonia, iron, and alkalinity measurements were taken during these tests. Dissolved iron levels were maintained between 1.5-3.0 mg/L. Total ammonia, nitrite and nitrate levels were monitored in order to visualize the overall health of the systems. Total ammonia and nitrite levels were not allowed to rise above 1 mg/L, because high levels of these constituents can cause adverse effects on the fish in the system. If ammonia or

nitrite levels became too high, the fish in the given system skipped a feeding or two until the levels dropped. (Nitrogenous fish waste is the cause for total ammonia and nitrite buildup.) Contrarily, nitrate is an essential source of nitrogen used by plants. Thus, it was necessary to keep nitrate levels high (>20mg/L). Consequently, all of the above measurements were taken regularly in order to find a balanced fish-feeding pattern, which would allow sufficient amount of nitrate to be produced without excessive buildup of nitrite.

Other conditions monitored during the experiment included humidity and temperature within each section. On average, the temperature for each section was maintained between 28 and 32 degrees Celsius. Slight variations in temperature between sections were caused due to the various lights being used in each section. Humidity was more variable than temperature, with measurements usually falling between 40% and 70%. Fans were used above each section to keep humidity levels constant, but levels still varied between sections.

Measurements

Each plant was numbered, and heights were measured in centimeters twice per week from the base of the plant (where roots started) to the top of the highest leaf. Plant heights were measured regularly throughout the 55-day experiment, but only final heights were used for results. The average wet weight of the plants was measured, in grams, before the study using a representative sample (10%) of the plants and averaging their weights. Weight for each plant was measured after the study and compared to the average original weight, as a way of measuring biomass growth during the project. The final weights of

plants that were grown under each light were averaged together and used for comparison against the initial average plant weight.

Each light source was connected to an energy meter, which measured total kilowatt hours (kWh) used per day. The kWh/day averages were used to calculate overall plant growth per kWh in $\text{g}/\text{m}^2/\text{kWh}$. This unit allowed for the comparison of total biomass growth (g) in a given area (m^2), per unit of energy (kWh). The amount of energy used by each light was also used to determine the cost to run each light throughout the study, using average energy costs for the residential sector of the state of Kentucky (provided by the U.S. Energy Information Administration).

Calculations

The final mean weights and heights of the plants of each section were calculated. The average biomasses from each light source, pooled across all four systems, were then compared to determine which light source encouraged the most growth.

Measurements for kWh/day were recorded for each light twice a week. After the experiment was concluded, the biweekly records were used to calculate the average kWh/day for each light. The energy meter on one LED light only recorded energy usage in watts, not kWh, so the following calculation was used to determine the kWh/day usage of this light:

$$\text{kWh} = (W \times T)/1000 ,$$

where kWh is the number of kilowatts used in a day, W is the watts/hour, and T is the total number of hours the lights were run per day (18 hours). Once the average number of kWh/day were calculated for each light, total kWh was calculated by multiplying kWh/day by the number of days the experiment lasted (55 days). Total biomass growth

under each light was then calculated by adding the overall biomass of the five plants in each section and subtracting by 45.5 g (five times 9.1g, the average weight of all plants initially). This measurement equated to g/m^2 because it represents the total net biomass growth per square meter, the area under each growth light. Finally, g/m^2 of each section was divided by the total kWh of each section to yield the total biomass growth per unit area per unit of energy ($\text{g/m}^2/\text{kWh}$) for each light in the four systems. Furthermore, the above results were averaged for each light source, and used to compare the total energy use and average $\text{g/m}^2/\text{kWh}$ for each type of light. These results were used to analyze which light source encouraged the most efficient plant growth.

Results

Weights and Heights

Overall plant growth was expressed in weight and plant height. The average initial heights and weights of the seedlings were 13.6 cm and 9.1 g, respectively. Plants grown under LED lights showed the most overall growth (Table 3). LED-grown plants had an average weight more than two times the weight of metal halide- and fluorescent-grown plants and outweighed induction grown plants by over 200 g. Furthermore, LED-grown plants resulted in the second highest average height. Together, the weights and heights indicate that LED-grown plants were more productive than plants growing under other types of lights. Metal halide-grown plants, on average, achieved the tallest plant height but had the lowest average weights. Fluorescent- and induction-grown plants had relatively similar plant weights; however, fluorescents were substantially shorter than the plants grown under any of the other light types (Table 3).

Table 3. Average weights (g) and heights (cm) of plants grown under each type of light.

Weights (g) Initial average weight: 9.1g				
	Light type			
System number	Induction	Metal halide	Fluorescent	LED
1	328.4	207.2	219.3	376.6
2	262.4	117.2	244.1	360.6
3	310.0	226.9	237.3	807.1
4	269.5	149.9	259.8	561.4
Average	292.6	175.3	240.1	526.4
Heights (cm) Initial average height: 13.6g				
	Light Type			
System number	Induction	Metal Halide	Fluorescent	LED
1	32.2	27.5	22.6	24.5
2	25.7	23.6	24.0	22.4
3	35.8	45.5	26.6	43.2
4	30.6	33.2	27.8	35.0
Average	31.1	32.5	25.3	31.3

Energy Use and Growth

On average, LED lights also produced the best growth rates (Table 4). However, LED lights averaged the most daily energy use and the highest overall energy usage. The LED lights used in this experiment varied greatly in their performance (Table 5). Even though all the LEDs were the same model, two lights used a large amount of energy, while the other two used much lower amounts of energy. The two LEDs using the least energy still yielded some of the largest total growths and growth rates. Consequently, LEDs were shown to be the light source most conducive to plant growth and also showed the *potential* to be more energy efficient than the averages from this experiment indicate.

After LEDs, induction lights yielded the highest amounts of net growth and growth rates (Table 4). Induction lights, on average, also had the lowest daily and total energy requirements. Metal halide and fluorescent lights also had relatively low energy requirements but yielded low total growth and low growth rates in comparison to LED and induction lighting. Thus, LED lights and induction lights induced the highest amount of total plant growth and produced the highest growth rates per amount of energy.

Table 4. Average energy usage, net growth and growth rate per light type.

	Light Type			
	IND	MH	FL	LED
Average Daily Energy Use (kWh/day)	2.67	3.07	3.13	3.66
Average Total Energy (kWh)	147.13	168.56	171.88	201.16
Average Net Growth (g/m ²)	1417.43	830.95	1140.55	2384.80
Average Growth Rate (g/m ² /kWh)	9.67	4.92	6.65	12.85

Table 5. Average energy usage, net growth and growth rate for each individual light.

	Light Type	Energy per Day (kWh/day)	Total kWh	Net Growth (g/m ²)	Growth Rate (g/m ² /kWh)
System 1	IND	3.02	166.10	1596.5	9.61
	MH	3.95	217.25	990.4	4.56
	FL	2.71	149.05	992.4	6.65
	LED	3.20	176.00	1837.3	10.44
System 2	IND	2.43	133.65	1266.5	9.48
	MH	2.02	111.1	540.5	4.86
	FL	2.98	163.90	1175.2	7.17
	LED	4.47	245.85	1757.6	7.15
System 3	IND	2.49	136.95	1504.6	10.99
	MH	3.64	200.20	1089.0	5.44
	FL	3.26	179.30	1141.2	6.36
	LED	4.62	254.10	3183.0	12.35
System 4	IND	2.76	151.80	1302.1	8.58
	MH	2.65	145.75	703.9	4.83
	FL	3.55	195.25	1253.4	6.42
	LED	2.34	128.70	2761.3	21.46

Lighting Costs

Cost analysis determined that LED lights used the greatest amount of total energy, followed by fluorescents (Table 6). Table 6 also shows the initial costs to purchase one of each type of light (The Aquaponics Source 2016). Costs of running each individual light were calculated by multiplying the total kWh used per light by \$0.1034, the average cost of energy per kWh in the state of Kentucky (EIA 2015).

The analysis showed that LED lights were the overall most expensive lights to power throughout the course of the experiment. However, not all of the light types were consistent in their energy use and cost (Table 7). For example, individual metal halide

lights cost between \$11.49 and \$22.46 to power over the duration of the experiment and individual LEDs cost between \$13.31 and \$26.27.

Table 6. Total cost and energy of each light type.

	IND	MH	FL	LED
Initial Purchase Cost for One Light (U.S. Dollar)	609.95 (200 W)	349.95 (250W)	149.95 (238 W)	699.95 (200 W)
Total Energy Used (kWh)	588.52	674.24	687.52	804.64
Total Energy Cost (U.S. Dollar)	60.85	69.72	71.09	83.20

Table 7. Energy cost for each individual light over the duration of the experiment.

	Light Type	Total kWh	Energy Cost (U.S. Dollar)
System 1	IND	166.10	17.17
	MH	217.25	22.46
	FL	149.05	15.41
	LED	176.00	18.20
System 2	IND	133.65	13.82
	MH	111.1	11.49
	FL	163.90	16.95
	LED	245.85	25.42
System 3	IND	136.95	14.16
	MH	200.20	20.70
	FL	179.30	18.54
	LED	254.10	26.27
System 4	IND	151.80	15.70
	MH	145.75	15.07
	FL	195.25	20.19
	LED	128.70	13.31

Discussion

Light Efficiencies and Potentials

The results from this experiment suggest that induction and LED lights are among the most efficient growth lights in aquaponics systems. This analysis is consistent with the literature (Martineau et al. 2012; Singh et al. 2014). At present, however, due to its efficiency and lower initial costs, fluorescent lighting may be a more popular light choice for aquaponics users (Vandre 2011).

LEDs have been shown to be an extremely efficient light source in multiple studies. Martineau et al (2012), found that Boston Lettuce grown under LED lights were on average the same size and weight as lettuce grown under High-Pressure Sodium (HPS) light sources, although LEDs applied only about half the amount of supplemental light as the HPSs. Their analysis showed no significant differences in the concentrations of most important pigments between plants grown under the different light sources. In terms of energy, they found that LED lamps provided an energy savings of at least 33.8% (Martineau et al. 2012).

LEDs convert up to 50% of energy into usable light, whereas many other light sources convert only around 30%. The rest of the energy is lost, mostly in the form of heat (Singh 2014). The high rate of light production per energy use suggests that LEDs could produce more photosynthetically available light than the other light sources. Additionally, Singh et al. (2014) found that greenhouse tomato growers can produce the same yield of tomatoes with 25% of the total energy after switching from other traditional lighting like HPS, to LEDs. Similar results were reported in other crops, such as cucumbers and lettuce (Mitchell 2012; Singh et al. 2014).

Some LED lamps are also capable of adjusting the spectrum of light they produce. Since plants absorb certain light more readily than others (i.e., red and blue light is absorbed more than green, yellow and orange), having lights that can produce particular light spectrums will be even more efficient in aquaponic systems (Singh et al. 2014). Fluorescent lights are also capable of being adjusted to produce light spectrums more suited to plant growth (Vandre 2011).

Cost Analysis

Cost determinations from this experiment showed that, of the four types of lights examined, LED lights are the most expensive initially and had the highest long-term energy costs. Induction lights, which this study showed to produce the second highest growth rate, were the second most expensive light for initial purchase; however, they yielded the lowest energy cost. Metal halide and fluorescent light both had significantly lower initial costs, but had relatively high energy costs paired with relatively low plant growth rates.

It is common for consumers to purchase lights based on initial prices (Sumper et al. 2012). However, these results show that the long-term costs of induction lighting could be much lower than the other sources because induction light costs are much lower than the other lights and studies have shown that induction lights often last much longer than other types of lights (Sumper et al. 2012). Metal halide and fluorescents, while they are cheaper to purchase, must be replaced more often and have higher energy costs.

One issue with a pure cost-analysis with this project, however, is that it does not take plant growth into account. For industrial aquaponics, it is ideal to reduce energy costs in order to increase profits. If looking only at the cost to power each light, then it would

appear that induction or fluorescent lights would be the best choice of light source because inductions are cheaper to operate in the long-run, while fluorescents are fairly inexpensive to operate with the lowest upfront cost. However, it is also important to take growth rates into account. LEDs, by far, produced the highest growth rates of the four light sources, followed by induction lighting, which again was far ahead of the other two (table 4). This is important to remember, because commercial aquaponics users will also be concerned with production. Since induction and LEDs produce the most plant growth, they are likely to produce more food in a shorter time frame. As a result, they have the potential to maximize income and profits of a commercial aquaponics operation, even with increased energy cost.

LED technology, as mentioned above, has been shown to have great potential to develop to be more efficient in the future. Some sources project that LEDs, due to their efficiency and continued technological development will become the primary light sources in the future lighting market (Sumper et al. 2012). With the extremely high growth rates they produce, if LED lighting becomes more energy efficient in the future, as projected, then it will be an ideal choice for aquaponics growers. However, until this potential is reached, it is likely that induction lighting would be most beneficial to aquaponics growers, due to the low energy costs and relatively fast growth rates. Additionally, inductions are less expensive initially than LEDs.

Need for Efficient Agricultural Techniques

In the last decades, increases in agricultural land use and productivity have led to a reduction of undernourished people. The percentage of undernourished people in developing regions declined from 24% from 1990-1992, to 14% in 2011-2013 (Fritsche

et al. 2015). However, the expansion of traditional agriculture has put a lot of pressure on cropland, causing it to degrade and lose its capacity to support abundant plant life. Furthermore, as the human population continues to increase, people are rapidly running out of available arable cropland to farm on to support the growing community (Despommier 2010). Thus, capacity to produce enough food to support the population is an area of growing concern.

Large cities currently occupy only 0.5% of global land area, and only 4% of arable land (Fritsche et al. 2015). Therefore, urban agricultural techniques, like aquaponics, could have minimal impacts on global land use if they were to become more abundant. Furthermore, expansion of urban agriculture would reduce the amount of ecological degradation from excessive use of fertilizers and pesticides, as well as reduce impacts of crop transport, because aquaponically-grown crops would be raised in close proximity to cities (Despommier 2010). The efficiency of aquaponics systems means they have potential to greatly increase local, urban food production and decrease reliance on traditional agriculture, thus alleviating some of the stress the growing population is placing on the environment. This is relevant because if increased energy efficiency could make aquaponics more economically feasible, then the energy efficiency of aquaponics could help reduce the waste and pollution of traditional agriculture.

Challenges of Commercial Aquaponics

Due to its efficient water use, aquaponics has the potential to be an important driver for the development of integrated urban food production systems, especially in arid regions (Goddek et al. 2015). However, large-scale aquaponics application faces multiple technical, as well as economic challenges (Goddek et al. 2015; Vermeulen and Kamstra

2013; Fritsche et al. 2015). Vermeulen and Kamstra (2013) found aquaponics to currently be a “suboptimal” agricultural alternative when compared to other methods, primarily due to the technological demands and disease management it requires. Securing land and infrastructure, and in some cases permits, for urban agriculture can also be a strenuous, expensive process, before the agricultural aspect is even employed (Fritsche et al. 2015).

Moreover, no major markets for aquaponic agriculture are currently in existence, thus financial reports for aquaponic businesses are scarce and often not open to the public (Goddek et al. 2015). Aquaponic agriculture as a business, therefore, will likely require meeting the challenges of finding a niche in the market, establishing supply chains, educating the public about the significance and potential of aquaponics systems, and ensuring consumers that aquaponically produced food is healthy and good tasting.

Most relevant to this study, meeting energy demands and costs are a challenge for large aquaponics systems once implemented. Lights, heat and cooling systems, and pumps must be constantly managed and maintained in order to produce the optimal conditions for efficient plant and fish growth (Goddek et al. 2015). Year round, steady temperature and light maintenance can be costly, especially in temperate regions, which is why the implications of this study are important.

This study suggest the use of induction and LED lighting in indoor aquaponics systems to encourage maximum plant growth and a reduction of energy costs. Increased light efficiency could significantly reduce the long-term energy costs associated with aquaponics systems, thus making aquaponics operations more economically sustainable and alleviating one of the challenges facing the implementation of these enterprises.

Experimental Error

The PAR measurements for LED lights varied greatly – constantly jumping from as little as 120 $\mu\text{mol}/\text{m}^2/\text{s}$, up to 240 $\mu\text{mol}/\text{m}^2/\text{s}$ – even while the meter was being held steady at the same distance from the light. It is possible that the PAR meter was accurate and the LEDs fluctuated in light intensity. However, it was assumed during the experiment that the meter was unable to measure the LEDs accurately. Consequently, LED lights were always placed 12 cm above the highest plant. (This distance was determined from the average of the fluctuating PAR readings when the meter was held at the level of the tallest plant.) Since the PAR readings for LED lights were so variable, the amount of PAR received by the plants under LEDs could have been more or less than the PAR plants received from other light sources. It is not understood exactly why the meter would not correctly measure PAR from LED lights. The meter did, however, measure steady readings for the other light sources, so all lights other than LEDs were adjusted accordingly to a level corresponding to 200 +/- 5 $\mu\text{mol}/\text{m}^2/\text{s}$.

Furthermore, approximately halfway through the experiment, aphids were noticed on some of the plants. Initially only a few aphids were noticed, so steps were taken to remove the aphids and prevent further infestation using insecticidal soaps. (Care was taken not to let the soaps drain into the water.) However, despite the control efforts, after a couple of weeks, aphids began to appear in large numbers in the majority of the systems. Around this time, the plants also began to show signs of nutrient deficiencies, such as discoloration and curled leaves. Although conclusions regarding the most effective types of grow lights for aquaponics systems were drawn from this experiment, it is possible that the compounded effects of aphids and nutrient issues altered the results.

Suggested Additional Studies for Aquaponics Efficiency

An additional challenge facing large-scale aquaponic implementation is the control of pests (Goddek et al. 2015). As aforementioned, this experiment experienced challenges with aphid infestation. No detailed assessment was conducted regarding aphid damage or the number of aphids on plants grown under different light sources. However, general observation seemed to indicate that aphids occurred more on plants growing under LED lights during this study. Thus, we suggest further behavioral studies be conducted on aphids and similar plant pests to determine if they show preference to any specific light sources over others. Such information could help build an understanding and awareness of potential challenges to aquaponics implementation.

Moreover, due to the inconsistencies in the LED lights observed in this experiment, further studies in LED lighting are needed to further assess LED lights as the most efficient light source in aquaponic systems.

Conclusion

This study suggests that induction and LED grow lights are most efficient in aquaponics systems in terms of their effects on overall plant growth and growth rates. Both were also found to be relatively energy efficient. Thus, I conclude that these light sources should be used in the implementation of aquaponic systems in the future to reduce the economic challenges associated with energy costs and maximize aquaponic production. Induction lighting may be favorable currently in aquaponic systems due to its high growth rates and low energy requirements. However, if LED technology can continue to produce high growth rates and total growth, as seen in this experiment, and

develop to use less energy, as has been project in other studies, then LEDs may be the most cost-efficient light source for aquaponic systems in the future.

I also suggest further study in this area to gather more knowledge about the efficiency of different light sources in terms of energy use and plant growth. Specifically, research is needed to determine if LED lighting can consistently produce high rates of plant growth with lower energy costs. Along with the literature, this study showed the potential for this, as different LED lights consumed varying amounts of energy – some used a lot, some very little.

Furthermore, I suggest studies on the relationship between plant pests and different types of growth lights to determine if plants grown under a specific type of light are more prone to being infested with pests. In other words, are pests more attracted to a particular type of light? The knowledge gained from these studies could increase the efficiency and production of aquaponic systems, thus making them more suitable for large scale implementation, which could drastically reduce the effects of human agricultural practices on the environment, as well as increase food production to help supply a growing population.

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