Market Analysis and Productivity of Aquaponics in Minnesota

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Abstract

Aquaponics, the combination of hydroponics and aquaculture into one growing system, continues to gain popularity on both a hobby and commercial scale. Many studies have been conducted to improve production methods, but few have examined consumer preferences for and attitudes toward aquaponics. The first chapter contributes knowledge to this area with results from an experimental auction that explored consumer preferences and identified potential market segments, with each segment having distinct preferences for produce grown in aquaponics systems. Using latent class analysis, participants were segmented into three classes. Two classes (totaling 70% of participants) were willing to pay more for aquaponically-grown lettuce than for the potting soil-grown counterparts; however, all bids were relatively low for a premium lettuce product. For all three segments, consumers' increased rating of lettuce appearance and flavor had a significant positive impact on their bids. Consumers willing to pay the highest price premium reported the highest environmental concerns and product quality. Typical horticulture aquaponic production focuses on leafy greens and herbs with no known studies on the production potential of strawberries (Fragaria ✕ananassa Duchesne) or any other perennial crop. The second chapter compares day-neutral strawberry yield of 'Albion', 'Evie 2' and 'Portola' in aquaponic productions with different variables of strawberry yield in greenhouse production using soilless medium. There was no addition of supplemental nutrients or pollinators to the systems in order to evaluate the differences between treatments. We found a significant difference among cultivars in number of fruit, fresh fruit weight, and dry fruit weight with 'Evie 2' having the highest yield in all. There was no significant difference in the number of fruit produced by strawberries grown in soilless medium and those grown aquaponically. We did, however, find that aquaponic strawberries had a significantly higher fresh fruit weight while strawberries grown in soilless medium had a significantly higher dry fruit weight. This indicates that strawberries grown in soilless medium have a higher mass to water ratio, although aquaponic-grown strawberries can have a higher fresh weight yield.

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CHAPTER 1:

Market Segmentation Analysis of Consumer Preference for Aquaponically Grown Produce (*Lactuca sativa*)

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Introduction

Aquaponics is the integration of aquaculture (raising aquatic animals, primarily fish) and hydroponics (the soilless growing of plants) that produces fish and plants together in one closed loop system (Rakocy, Masser, and Losordo 2006). In general terms, the fish waste provides a nutrient source for the growing plants, and the plants provide the elimination of toxic ammonia build up for the water in which the fish live (Diver and Rinehart 2006). There is no standard aquaponic set-up; systems vary greatly in terms of size, substrate, water flows, crops, and many other factors. This makes them ideal, in terms of flexibility, for urban farming since they can be modified to fit almost any space or need (Goddek et al. 2015).

Aquaponic production has increased tremendously in popularity over the last decade to capitalize on changing consumer preferences (Love et al. 2014). Industry growth is expected to exceed 10% total by 2020 ("Aquaponic Farming: Global Market Intelligence" 2016). Urbanization, population growth, environmental and health concerns are a fraction of the many factors that are leading some consumers to demand more locally-grown food (Hundley and Navarro 2013). As the trend of eating locally-produced food has increased over the last decade (Ruth-McSwain 2012) so has the popularity of urban farming. Urban farming is utilizing space in urban areas, such as rooftops, vacant warehouses, or yards, that would not be suitable for traditional agriculture to grow food (Hashim 2014). This can manifest in small ways such as a backyard garden or on a larger scale such as an aquaponic warehouse facility. In cold climates, due to freezing winters, year-round urban farming production is confined to indoor growing facilities, such as greenhouses and warehouses.

Aquaponics has numerous other potential benefits beyond adaptability. Implementing aquaponics in an urban farming landscape could use 90% less water than conventional produce growing methods (Dalsgaard et al. 2013). In addition, since the only water lost in aquaponics is due to evaporation and fish/plant respiration within the closed-loop system, environmental contamination is not an issue. Urban aquaponics could also increase shelf life of produce and reduce the risk of food borne illness (Sirsat and Neal 2013;Shaalan et al. 2018). Overall carbon emissions could also be reduced because of the shorter distances needed to transport the goods (Bernstein 2011). Some aquaponic set-ups are also able to increase planting densities with an increase in both harvest and space efficiency (Suhl et al. 2016).

The most limiting factor of aquaponic industry success is higher operational and start-up costs as compared to traditional growing methods (Karimanzira et al. 2017). Raising the price of produce is the most straightforward way to increase revenue and cover costs, especially since economic success of aquaponic producers is most sensitive to produce price (Tokunaga et al. 2015). The question then becomes, are consumers willing to pay a premium for aquaponic produce and, if so, how much? Furthermore, are there specific groups of consumers who are willing to purchase and pay price premiums for aquaponics produce and if so, who are they?

There have been limited previous studies on consumer willingness to pay (WTP) for aquaponic produce, especially in the United States. Studies specific to aquaponic produce have been conducted across Europe (Milicic et al. 2017), Germany (Specht et al. 2016), Malaysia (Tamin et al. 2015), and Romania (Zugravu et al. 2016). Those that have been conducted focused on consumer knowledge and attitude of aquaponics but do not further identify consumer segments.

The European studies on consumer attitudes toward aquaponic produce found similar results. Less than half of respondents had heard of aquaponics and their general attitude towards aquaponics was neutral. The way in which aquaponics is introduced to consumers seemed to play a key role in determining consumer preferences. For example, Milicic et al. (2017) provided a positive definition of aquaponics to respondents and received positive responses from respondents. Zugravu et al. (2016) found that positive responses to aquaponics were more likely when respondents were asked to consider the local and organic aspects of aquaponic systems. German consumers were willing to purchase produce grown in urban farming systems as long as urban farming was similar to traditional farming. Specht et al. (2016) found that over 50% of respondents were willing to buy urban grown produce, but 65% of them also rejected multistory aquaponic farms. The environmental benefits of aquaponics appealed to European consumers, but the industrialization aspect did not. Malaysian consumers had a more positive view of aquaponics in general but they considered “green products” and local production to be the most important aspects of their purchase (Tamin et al. 2015).

A recent study based on the same experiment used in this analysis evaluated consumers' WTP for lettuce samples before and after they were told if the samples were grown aquaponically (Short et al, 2018). The study found no significant differences in average bids between aquaponic lettuce and the potting soil grown counterparts. However, the study noted that bids for the aquaponic samples varied significantly depending on the lettuce variety and whether they were grown in a greenhouse or warehouse. While on average the aquaponic lettuce did not garner a premium price, one specific lettuce variety grown in an aquaponic warehouse did. The current study picks up where Short et al. (2018) left off and explores if market segmentation can shed more light on preferences for aquaponic produce.

Materials and Methods

Participants were recruited by posting advertisements in 13 local newspapers that ran across the urban and suburban areas of Minneapolis and Saint Paul, Minnesota. The screening requirements for potential participants were self-reported regular buyers of produce who were at least 18 years of age. The study took place over two weekends in December 2016. Participants were placed in groups of 10-12 for the hour-long sessions. In total, we had 91 participants grouped into eight sessions. One participant's responses were dropped due to incomplete information.

We ran Vickrey second-price auctions to elicit consumers' WTP (Vickrey 1961). Vickrey auctions are private auctions where participants do not know others' bids before they submit their bids. This method was chosen in order to reduce the possibility of over-or under-bidding. It has been proven that Vickrey auctions are incentive compatible, that is, people submit bids that sincerely reflect their true value for the goods (Yue, Hurley, and Anderson 2011). For the second-price auction, the highest bidder wins the auction, but only has to pay the second highest price. Those with winning bids took home the head of lettuce they won after paying the bid from their compensation. Participants were compensated $40 for those who did not win an auction and $40 minus the winning bid for those who did win.

Participants bid on nine different 8-ounce (227g) heads of lettuce. Three different cultivars of green lettuce were selected for this experiment, ‘Salanova® Green Sweet’, ‘Salanova® Green Incised’, and ‘Rex Butterhead’. Each were grown in three different conditions (treatments): greenhouse potted soilless medium, Sunshine brand LC8 potting mix (Sun Gro Horticulture, Agawam, MA), greenhouse aquaponics (Koi fish), or warehouse aquaponics (Koi fish); 3 cultivars X 3 treatments = 9 samples. The main difference between the aquaponic treatments was that warehouse aquaponic plants were grown with entirely artificial light (low emitting diodes, LEDs, Agrivolution LLC, http://www.agrivolution.co), whereas greenhouse aquaponic plants were grown with natural sunlight. Samples of each lettuce (individual leaves) were given to participants so they could examine and taste the lettuce more easily. Each sample had a corresponding head of lettuce on display so that participants could closely examine its appearance.

After the auction procedure was explained, example questions related to the auction mechanism were given to participants. Answers to these questions were announced afterwards to help participants understand the mechanism. After participants examined and tasted each sample, they rated six attributes (overall liking, appearance, flavor, crispness, texture, and aroma) on a 7-point scale regarding the degree of how much participants liked the attribute in each sample with a range from “Dislike very much” to “Like very much.” A seventh attribute (bitterness/mildness) had a 7-point scale that ranged from “Extremely mild” to “Extremely bitter”. They then placed a bid for each sample. Participants were not informed of the growing conditions for the first round of bidding.

After the first round of bidding, it was then explained what aquaponics was and which samples had been grown under what conditions. The brief, neutral definition of aquaponics was given to participants as follows: “*Some of the lettuces are aquaponically-grown. Aquaponics is the integration of aquaculture (raising fish) and hydroponics (the soil-less growing of plants) that grows fish and plants together in one system. The fish waste provides a food source for the growing plants and the plants provide a natural filter for the water the fish live in.*” Participants were then told to bid a second time on each lettuce sample. The session then ended with a survey on participants’ demographics and attitudes towards aquaponics.

The attitudinal survey had 50 questions total in three different sections using 7-point rating scales[1]. The first section contained 15 statements and asked, “How much do you agree with the following attitudinal statements about aquaponics” with the scale ranging from “Strongly Disagree” to “Strongly Agree.” The second section asked, “How important to you are the following statements about aquaponic production compared to

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[1] Full survey instruments can be made available by the authors upon request.

conventional soil production" where the scale ranged from "Very Unimportant" to "Very Important." This section contained 14 different statements. The third section contained 21 statements and posed the question, "When thinking about aquaponic agricultural system and aquaponically grown produce, how much are you concerned with the following aspects" with the scale ranging from "No concern at all" to "Extremely concerned".

Factor analysis was applied to the attitudinal survey questions. Factor analysis is used to consolidate multiple variables into new variables while still keeping as much variation of the original data as possible (Jolliffe 1986). Questions were consolidated into factors. Questions with standardized regression coefficients higher than .4 in more than one factor were eliminated in order to determine distinctive factors without significant overlap. Three factors were determined using the Scree test (Cattell 1966). Refined factor scores were assigned to each participant and included as a variable in the following segmentation analysis. Factor scores are composite variables which represent each participant's placement in each factor (Distefano and Mîndril 2009). Factor scores were calculated using software SAS 9.4 (Cary, North Carolina).

Latent Class Analysis (LCA) was then used to separate participants into different classes of consumer. LCA is used to measure indirect, or latent, variables using observable indicator variables (Collins and Lanza 2009). LCA is used most in social sciences and other fields to explore underlying consumer segments in terms of their preferences for various products (Bartholomew 2011).

Suppose there are N consumers with G latent homogeneous classes and the latent variable $c_i = \boldsymbol{g}$ if consumer i ($i=1, \ldots, N$) belongs to class g ($g=1,\ldots, G$). The probability of latent class membership can be explained through covariates X_{1i} using multinomial logistic regression:

$$\pi_{ig} = P(c_i = g \,|\, \boldsymbol{X_{1i}}) = \frac{e^{\gamma_{0g} + \boldsymbol{\gamma_{1g} X_{1i}}}}{\sum_{m=1}^{G} e^{\gamma_{0m} + \boldsymbol{\gamma_{1m} X_{1i}}}} \qquad (1)$$

where $\boldsymbol{X_{1i}}$ is a row vector of consumer i's socio-demographics, attitudes, or past experiences; $\gamma_{0G}=0$ and $\boldsymbol{\gamma_{1G}} = \boldsymbol{0}$, that is, class G is the reference class.

Consumer i's WTP for product j ($j=1, \ldots, J$) is estimated using the following linear regression:

$$Bid_{ij}|_{c_i=g} = \boldsymbol{X_{2ij}\beta_g} + \varepsilon_{ij} \qquad (2)$$

where Bid_{ij} is consumer i's bid for the product j in the experimental auction, $\boldsymbol{X_{2ij}}$ is a row vector of product j's attributes consumer i bids on; $\boldsymbol{\beta_g}$ is a column vector of coefficients associated with the product attributes for latent class g; ε_{ij} is the residual error term which follows standard normal distribution with mean zero and variance σ_{ε}^2.

The log-likelihood function is

$$ll = \sum_{i=1}^{N} ln \sum_{g=1}^{G} P(c_i = g|\boldsymbol{X_{1i}})\varphi_{ig}(\boldsymbol{Bid_i}|c_i = g; \boldsymbol{X_{2i}})$$

(3)

where $\boldsymbol{X}_{2i}$ and $\boldsymbol{Bid_i}$ are matrices of *J* row vectors of $\boldsymbol{X}_{2ij}$ and Bid_{ij} respectively; φ_{ig} is the pdf of multivariate normal distribution with mean $\boldsymbol{X}_{2i}\boldsymbol{\beta_g}$ and variance matrix $\sigma_\varepsilon^2 I_J$; I_J is a *J X J* identify matrix (Verbeke and Lesaffre 1996; Proust and Jacqmin-Gadda 2005). The estimation was conducted using software R 2.13.2 (Boston, MA, USA).

Results

A summary of participant demographics can be found in Table 1. All participants had a high school education or greater and 19% had a graduate degree. The majority of participants, 69%, identified as female. The average age was within the range of 41-60 years old; 67% were either married or had a partner and the average household size was 2.33 people. Eighty-three percent of participants reported shopping for produce once a week or more[2].

We did not find a significant difference between bids of potting soil-grown and aquaponically-grown lettuce (Short et al. 2018). The average bid for all potting soil-grown samples was $1.48 while the average bid for all aquaponically-grown samples was $1.47. This does not distinguish between samples grown in the aquaponic greenhouse and those grown in the aquaponic warehouse. However, aquaponic treatments were distinguished in the current analysis in order to determine if aquaponic treatments had an effect on consumer WTP.

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[2] We used slightly different demographic categories than in Short et al. (2018) in order to capture the significant differences of consumer WTP across the different segments.

As seen in Table 2 three factors explained 97% of the variance in the attitudinal survey, and inter-factor correlations were all less than 0.18. Factor 1, which accounted for 50% of the attitudinal survey answer variability within the analysis as seen in Table 2, was characterized by participants who thought that it was very important for aquaponic production to be more productive, energy efficient, and well suited to urban environments compared with conventional production. Factor 1 was named ‘environmentally concerned.’ Factor 2 explained 34% of the variance, and was characterized by the high importance of appearance, freshness, and fewer blemishes on produce. Factor 2 was named ‘product focused.’ Factor 3 accounted for 13% of the variance and was characterized by high levels of concern for nutrition, chemical residue, and genetic modification in aquaponic production. Factor 3 was named ‘health focused.’

Each participant was assigned a factor score, which was their relative probability of choosing similar answers to other participants on the same questions. Participants with a high score in factor 2 were unlikely to answer similarly to participants with a high score in factors 1 or 3.

Results of the Latent Class Analysis are presented in three tables: summary characteristics of the consumer classes (Table 3), class membership (Table 4) and product attribute (Table 5). The class membership table (Table 4) presents coefficient results for each segment’s demographic variables of. The coefficients represent the relative likelihood of a participant with certain demographic characteristics being in each class (with class 3 as the base for comparison). The product attribute table (Table 5) presents coefficients for the lettuce attributes or lettuce attribute ratings.The second section presents cultivar coefficients use ‘Rex Butterhead’ as the comparison and represent the difference between ‘Rex Butterhead’ and the listed cultivar. In the third section, growing condition coefficients use potting soil as the base for comparison and represent the difference in bid between potting soil and the listed growing condition.

Using the significant results from the class membership classification and product attribute tables (Tables 4 and 5), we classified participants into three latent market segments. The summary characteristics of the consumers in the three segments are shown in Table 3. Class 1 accounted for 28% of participants and was characterized by consumers who infrequently purchased produce (more likely to purchase produce less than once a week) (Table 4). Neither growing conditions, nor lettuce attributes beyond appearance and flavor had an impact on this segment’s WTP (Table 5). Class 1 was named *Indifferent Consumers*, to reflect these characteristics.

Class 2 accounted for 56% of participants. These consumers are less likely to have a large household, full time job, or be product focused or environmentally concerned (Table 4). Class 2 participants have increased WTP for aquaponically-grown lettuce as long as it is the ‘Rex Butterhead’ cultivar (Table 4), which is the cultivar the most closely resembles common ‘Iceberg’ lettuce. Class 2 was named *Conventional Consumers.* Class 3 accounted for the remaining 16% of participants. Class 3 consumers were not likely to be in any particular demographic but exhibited environmental concerns and considered product quality as significantly (at .05 significance scale) more important than *Indifferent Consumers* and *Conventional Consumers*. They had the highest WTP for aquaponically-grown produce of the three classes and were named as *Aquaponic-Liking Consumers* to reflect their increased WTP for aquaponically-grown lettuce.

Indifferent Consumers had the lowest average bid for all lettuces (both aquaponic and potting soil grown), $1.35. *Conventional Consumers* had an average bid of $1.44. *Aquaponic-Liking Consumers* had the highest average bid, $1.58. Table 4 presents the coefficients of demographic characteristics for each class of consumers, using the coefficients for *Aquaponic-Liking Consumers* as the base for comparison. As shown, *Conventional Consumers* were significantly less likely (at the 95% significance level) to have a full-time job than *Aquaponic-Liking Consumers*. They are also less likely (at the 95% significance level) to be living in a household with five or more people. Neither age, income, gender, marital status, nor education level was significantly different between consumer segments. *Conventional Consumers* were significantly less likely to be product focused and environmentally concerned than *Aquaponic-Liking Consumers*.

As shown in Table 5 increased appearance and flavor ratings had a positive impact on WTP (significant at 95% or higher) to all three types of consumers in determining their bids. Likewise, increases in bitterness (which can be a negative attribute) had a negative impact on participants' bids. An increase in lettuce texture rating significantly positively affected *Conventional Consumers'* bids. The higher the aroma rating (which means the stronger the aroma), the lower the bids for *Conventional Consumers* and *Aquaponic-Liking Consumers*. It indicates participants in these two segments did not like intense aroma in lettuces. *Conventional Consumers* also showed stronger preferences for 'Rex Butterhead' lettuce as indicated by the significant (at the

99% significance) lower bids for the other cultivars. *Indifferent Consumers* had no significant preferences for other lettuce attributes beyond an increase in WTP for improved appearance and flavor, and a decrease in WTP for increased bitterness. *Aquaponic-Liking Consumers* disliked ‘Salanova Sweet’ lettuce as compared to ‘Rex Butterhead.’ Crispness also significantly positively impacted *Aquaponic-Liking Consumers’* bids. *Conventional Consumers* and *Aquaponic-Liking Consumers* bid significantly higher for warehouse aquaponically-grown lettuce than potting soil-grown lettuce.

Discussion and Conclusions

Aquaponic production has increased in popularity in recent years, yet few studies have explored potential market segments for consumer preferences for produce grown in aquaponics. Using experimental auctions and latent class segmentation analysis, this study fills this knowledge gap and our results have important marketing implications. We identified three consumer segments with distinct preferences for lettuce grown in aquaponic production systems.

Based on the findings from the market segmentation analysis, some general conclusions can be drawn about the types of consumers most likely to pay a higher price for aquaponically grown lettuce. Aquaponic producers hoping to increase revenue using a price premium need to focus their marketing on the environmental benefits of aquaponics while maintaining a high-quality product.

Aquaponic-Liking Consumers were the most responsive to environmental concerns and product quality. They were likely to work full time and have household sizes greater than four people. They were also the most willing to pay for aquaponically-grown lettuce, nearly $0.30 more per 8 ounces. *Aquaponic-Liking Consumers* had an aversion to strong aroma and crispness but favored flavor and appearance of the lettuce samples. Though only making up 16% of participants in this study *Aquaponic-Liking Consumers* were the most receptive to aquaponically-grown lettuce and had the highest WTP.

The *Conventional Consumer* segment accounted for over half of all participants in this study. *Conventional Consumers* seemed to be willing to pay more for their favorite lettuce cultivars, possibly those that most closely resemble familiar cultivars. In this case, participants preferred ‘Rex Butterhead’, which is the most similar in appearance and texture to lettuce cultivars commonly sold in the grocery store, such as ‘Iceberg’. *Conventional Consumers* are most likely to have a small household and least likely to have a full-time job. In addition to appearance and flavor, texture positively affected their WTP. They indicated tolerance for lower product quality traits such as blemishes, and apathy for environmental importance. *Conventional Consumers* were willing to pay $0.17 more for 8-ounce head of lettuce that was grown aquaponically than the equivalent head grown in potting soil (Table 5). It is interesting to note how both *Conventional Consumers* and *Aquaponic-Liking Consumers* were willing to pay more for aquaponically-grown lettuce but had differing attitudes towards environmental issues.

This could be because the *Conventional Consumers* would prefer to buy lettuce most closely resembling what they are familiar with regardless of how it was grown.

The *Indifferent Consumer* segment is made up of consumers who buy produce less than once a week and have no specific preferences for their product beyond appearance and flavor. These shoppers are easy to please but have the lowest average bid among the three consumer segments. *Indifferent consumers* make purchases based on looks and taste, not on attributes they cannot see, such as growing conditions.

In general, consumers have shown limited knowledge of aquaponics across many studies. A survey conducted in Minnesota in 2016 by Short et al. found even fewer consumers, one third of respondents, had heard of aquaponics (Short et al. 2017). Results of a European consumer survey conducted in 2016 by Milicic et al. (2017) indicated that more than half of all respondents did not know what aquaponics was and, of those who did only 17% of them said they would be willing to pay more. In a 2015 German survey only 27% of respondents approved of aquaponics (Specht et al. 2016). Educating consumers about aquaponic benefits could increase their interest and enlarge the market size. Determining which specific consumers would be most receptive to learning about aquaponics would help in adopting target marketing strategies.

Previous surveys (Short et al. 2017; Milicic et al. 2017) have found price to be a concern for consumers when considering aquaponic produce. A consumer survey on hydroponic tomatoes ranked price as the third most important factor following place of purchase and perceived quality (Padilla et al. 2007). This study estimated the price premiums participants from different segments were willing to pay for aquaponically-grown lettuces, which helps suppliers determine how much they should charge for their products when they are targeting different consumer segments.

Participants in this study were not made aware of if the aquaponic lettuce samples were grown in a greenhouse or a warehouse. They made their bids merely based on their tasting and examination. The descriptive statistics in Short et al. (2018) reported significantly higher WTP for warehouse-grown aquaponic lettuce compared to greenhouse-grown aquaponics lettuce. The current study also found the preference for aquaponic lettuce grown in a warehouse. Future studies should be conducted to investigate the potential WTP change caused by the differences between the natural light of the greenhouse and the fully artificial light of the warehouse and how to improve product quality.

Short et al. (2018) found that being a member of an environmental group had a significant negative impact on consumer WTP for aquaponic lettuce. This study validated the result by finding increased environmental concerns in *Conventional Consumers*' decreased their WTP. However, the environmental concern factor did not significantly affect *Aquaponic-liking Consumers*' WTP. This might be because of *Conventional Consumes*' lack of knowledge on aquaponic environmental benefits or because of their association of aquaponics with industrialization as Specht et al. (2016) suggested.

Table 1-1: Summary statistics of participant demographics (age, gender, income, education, employment status, marital status, household size) in the aquaponic lettuce experiment (N=90)

Categories	Frequency	Percent of sample
Age		
Ages 18-40 years	15	17%
Ages 41-60 years	30	33%
Ages 61+ years	45	50%
Gender		
Male	27	31%
Female	61	69%
Income		
Income $50,000 and under	39	43%
Income $50,001-$100,000	36	40%
Income $100,001 and over	15	17%
Education		
High school or college degree	73	81%
Graduate degree	17	19%
Employment status		
Retired/student/unemployed	49	54%
Full time job	26	28%
Part time job	15	16%
Marital status		
Not single	60	67%
Single	30	33%
Shopping frequency for produce		
Less than once a week	15	17%
Once a week or more	75	83%
Household size		

Less than 5	81	90%
5 or more	9	10%

Table 1-2: Variance, and cumulative variance for sorted factors of the attitudinal survey and the matrix of inter-factor correlations.

	Variance	**Cumulative Variance**
Factor 1	0.50	0.50
Factor 2	0.34	0.84
Factor 3	0.13	0.97

Inter-Factor Correlations

	Factor 1	**Factor 2**	**Factor 3**
Factor 1	1.00	0.17	-0.08
Factor 2	0.17	1.00	0.14
Factor 3	-0.08	0.14	1.00

Table 1-3: Summary of demographic traits and attribute preferences by consumer segment

Consumer Segment	**Demographic Traits**	**Attribute Preferences**
Class 1 ***Indifferent Consumers*** (28%)	• Infrequent shopper	• Appearance • Flavor
Class 2 ***Conventional Consumers*** (56%)	• Small household • Least environmentally concerned • Least concerned about product quality • Not working full time	• Appearance and flavor • Texture important • Dislike of strong aroma • Preference for ‘Rex Butterhead’ • Increased WTP for warehouse aquaponically-grown lettuce
Class 3 ***Aquaponic-Liking Consumers*** (16%)	• Most environmentally concerned • Most concerned about product quality • Works full time • Large household	• Appearance and flavor • Dislike of strong aroma and crispness • Dislike of ‘Salanova Sweet’ • Largest increase in WTP for warehouse aquaponically-grown lettuce

Table 1-4: Latent class analysis for the demographic estimates of participants in this study

Categories	Coefficient	Standard Error
Intercept *Indifferent Consumers*	1.05	(1.60)
Intercept *Conventional Consumers*	3.24**	(1.48)
Intercept *Aquaponic-Liking Consumers*	-	-
Age		
Ages 18-40 years	-	-
Ages 41-60 years *Indifferent Consumers*	-1.41	(1.28)
Ages 41-60 years *Conventional Consumers*	-0.33	(1.27)
Ages 41-60 years *Aquaponic-Liking Consumers*	-	-
Ages 61+ years *Indifferent Consumers*	-0.77	(1.43)
Ages 61+ years *Conventional Consumers*	-0.74	(1.37)
Ages 61+ years *Aquaponic-Liking Consumers*	-	-
Gender		
Male	-	-
Female *Indifferent Consumers*	1.30	(0.97)
Female *Conventional Consumers*	0.73	(0.90)
Female *Aquaponic-Liking Consumers*	-	-
Income		
$50,000 and under	-	-
$50,001-$100,000 *Indifferent Consumers*	-0.02	(1.23)
$50,001-$100,000 *Conventional Consumers*	-0.46	(1.07)
$50,001-$100,000 *Aquaponic-Liking Consumers*	-	-
$100,001 and over *Indifferent Consumers*	1.99	(1.53)
$100,001 and over *Conventional Consumers*	1.85	(1.44)
$100,001 and over *Aquaponic-Liking Consumers*	-	-

Education		
High school or college degree	-	-
Graduate degree *Indifferent Consumers*	-0.22	(0.90)
Graduate degree *Conventional Consumers*	-0.40	(0.85)
Graduate degree *Aquaponic-Liking Consumers*	-	-
Employment		
Retired/student/unemployed	-	-
Full time job *Indifferent Consumers*	-1.28	(1.12)
Full time job *Conventional Consumers*	-2.51**	(1.08)
Full time job *Aquaponic-Liking Consumers*	-	-
Part time job *Indifferent Consumers*	-0.84	(1.28)
Part time job *Conventional Consumers*	0.13	(1.07)
Part time job *Aquaponic-Liking Consumers*	-	-
Relationship Status		
Single	-	-
Not single *Indifferent Consumers*	0.00	(0.09)
Not single *Conventional Consumers*	-0.95	(0.70)
Not single *Aquaponic-Liking Consumers*	-	-
Shopping Frequency		
Once a week or more	-	-
Less than once a week *Indifferent Consumers*	2.35 *	(1.40)
Less than once a week *Conventional Consumers*	1.07	(1.40)
Less than once a week *Aquaponic-Liking Consumers*	-	-
Household Size		
Household under 5 people	-	-
Household 5 or more people *Indifferent Consumers*	-2.08	(1.38)
Household 5 or more people *Conventional Consumers*	-2.37**	(1.14)
Household 5 or more people *Aquaponic-Liking Consumers*	-	-
Factors		
Environmentally concerned factor *Indifferent Consumers*	-0.98	(0.71)

Environmentally concerned factor *Conventional Consumers*	-1.39**	(0.69)
Environmentally concerned factor *Aquaponic-Liking Consumers*	-	-
Health focused factor *Indifferent Consumers*	-0.10	(0.77)
Health focused factor *Conventional Consumers*	1.08	(0.77)
Health focused factor *Aquaponic-Liking Consumers*	-	-
Product focused factor *Indifferent Consumers*	0.40	(0.77)
Product focused factor *Conventional Consumers*	-1.20*	(0.74)
Product focused factor *Aquaponic-Liking Consumers*	-	-

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 1-5: Latent class analysis estimates in US dollars

Category	Coefficient	Standard Error
Intercept *Indifferent Consumers*	NA	NA
Intercept *Conventional Consumers*	1.53***	(0.37)
Intercept *Aquaponic-Liking Consumers*	3.26***	(0.58)
Lettuce Attributes		
Appearance rating *Indifferent Consumers*	0.07**	(0.04)
Appearance rating *Conventional Consumers*	0.09***	(0.03)
Appearance rating *Aquaponic-Liking Consumers*	0.34***	(0.05)
Flavor rating *Indifferent Consumers*	0.24***	(0.04)
Flavor rating *Conventional Consumers*	0.30***	(0.03)
Flavor rating *Aquaponic-Liking Consumers*	0.42***	(0.06)
Crispness rating *Indifferent Consumers*	0.07	(0.05)
Crispness rating *Conventional Consumers*	0.03	(0.03)
Crispness rating *Aquaponic-Liking Consumers*	0.03*	(0.03)
Texture rating *Indifferent Consumers*	0.08	(0.05)
Texture rating *Conventional Consumers*	0.16***	(0.03)
Texture rating *Aquaponic-Liking Consumers*	0.08	(0.05)
Aroma rating *Indifferent Consumers*	-0.03	(0.04)
Aroma rating *Conventional Consumers*	-0.13***	(0.04)
Aroma rating *Aquaponic-Liking Consumers*	-0.23***	(0.06)
Bitterness rating *Indifferent Consumers*	-0.06*	(0.03)
Bitterness rating *Conventional Consumers*	-0.04*	(0.02)
Bitterness rating *Aquaponic-Liking Consumers*	-0.09*	(0.05)
Lettuce Cultivars		
Rex *Indifferent Consumers*	-	-
Rex *Conventional Consumers*	-	-
Rex *Aquaponic-Liking Consumers*	-	-
Salanova Sweet *Indifferent Consumers*	-0.02	(0.12)
Salanova Sweet *Conventional Consumers*	-0.30***	(0.08)
Salanova Sweet *Aquaponic-Liking Consumers*	-0.74***	(0.16)

Salanova Incised *Indifferent Consumers*	0.00	(0.15)
Salanova Incised *Conventional Consumers*	-0.32***	(0.09)
Salanova Incised *Aquaponic-Liking Consumers*	-0.24	(0.17)
Growing Conditions		
Potting soil grown *Aquaponic-Liking Consumers*	-	-
Potting soil grown *Conventional Consumers*	-	-
Potting soil grown *Indifferent Consumers*	-	-
Aquaponic greenhouse grown *Indifferent Consumers*	-0.00	(0.12)
Aquaponic greenhouse grown *Conventional Consumers*	-0.02	(0.09)
Aquaponic greenhouse grown *Aquaponic-Liking Consumers*	-0.19	(0.16)
Aquaponic warehouse grown *Indifferent Consumers*	-0.03	(0.12)
Aquaponic warehouse grown *Conventional Consumers*	0.17**	(0.08)
Aquaponic warehouse grown *Aquaponic-Liking Consumers*	0.30**	(0.16)

Standard errors in parentheses

$^{*} p < 0.10$, $^{**} p < 0.05$, $^{***} p < 0.01$

CHAPTER 2:

An Analysis of Strawberry (*Fragaria* X *ananassa)* Productivity in Northern Latitudinal Aquaponic Growing Conditions

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Introduction

Aquaponics is the integration of hydroponics (the soilless growing of plants) and aquaculture (the raising of fish) into a closed-loop, recirculating system (Rakocy, et al., 2006). The fish waste provides a nutrient source for the plants and the plants provide the elimination of toxic ammonia build up for the water in which the fish live (Rakocy et al., 2006). The only nutritional input (food or nutrients) into the system is fish food. Fish then excrete waste which is converted into plant available nutrients (nitrates) by nitrifying bacteria in a biofilter and taken up by the plants (Diver and Rinehart, 2006).

Aquaponics developed as a way to control waste water from recirculating aquaculture systems (RAS) (Costa-Pierce et al., 1997). Though RAS has many benefits, water conservation is not one of them and there was a demand to develop a cost effective filtration system. Plants can be used as filters for RAS wastewater and also as a secondary crop which led to the development of closed loop aquaponic systems (Rakocy et al., 2006; Lewis, 1978). There was also a motivation from hydroponic growers to develop more cost effective and environmentally friendly nutrient solution sources (Rakocy et al., 2007).

Aquaponic production is the fastest growing sector of agriculture (Kloas et al., 2015), in part, due to pressure from population growth, drought, and increased water demand (Hundley and Navarro, 2013). Total aquaponic industry growth worldwide is expected to exceed 10% by 2020 (Aquaponic Farming: Global Market Intelligence, 2016). Urban agriculture, including aquaponics, is continuing to grow with over 100 million growers estimated (Eigenbrod and Gruda, 2015).

Most aquaponic producers are considered small farms both in size and revenue (Love et al., 2014). Aquaponic systems can vary dramatically in scale, system design, plant crops, fish species and management procedures. The type of system ultimately chosen is dependent on the location, production goals, market demand, and many other factors although the vast majority are in controlled environments such as greenhouses (Love et al., 2015); warehouses have also been used. The most common commercial aquaponic system is called deep water culture (DWC), where the plants and fish are physically separated and the plants grow on floating rafts with their roots suspended in the nutrient-rich water (Taiz, 2010).

Commercial aquaponic growers also use ebb and flow systems in which the plant roots are intermittently submerged in water, though it is less common than DWC. The other types of systems, e.g. aeroponic and nutrient film techniques, are rarely used in aquaponic production because of issues with solids clogging the system (Søberg, 2016).

Strawberries (*F.* ✕*ananassa*, Rosaceae) are an herbaceous, perennial crop that grow relatively close to the ground (maximum 30cm tall) and spread both by seed and vegetatively via stolons (Vincent et al., 1990). Flowers grow in clusters on individual stocks to an even height or slightly above the foliage and bloom successively (*Cold Climate Strawberry Farming*, 2014). The first bud to flower is called the ‘king flower’ and is significantly larger than subsequent flowers on the cluster; resultant fruit from this are termed ‘king berries’. Subtending lateral fruits are smaller in size. Flowers have both stamens and pistils and are able to self-pollinate although complete pollination and fruit fill requires additional stimulation besides wind (Vincent et al., 1990). The fruit is an aggregate accessory fruit and is formed from the receptacle, which holds the ovary; the sum of these receptacles forms the strawberry fruit.

Strawberries are classified by their photoperiodic response into three categories. June-bearing cultivars need short day lengths (<12 hr) in order to flower, ever-bearing cultivars need long day lengths (>12 hr) in order to flower, and day-neutral cultivars are not affected by day length. June-bearing strawberries produce only one large crop of fruit in the spring and are currently the most popular choice for northern latitude farmers because of their ability to overwinter (*Cold Climate Strawberry Farming*, 2014). However, day-neutral cultivar popularity has been growing in northern latitudes with the increase in season extension (high tunnels and low tunnels) and climate controlled production (Petran et al., 2017). The day-neutral cultivars ‘Portola’ and ‘Albion’ are recommended for outdoor production due to their high yields, large fruit size, and sweet fruit (Petran et al., 2017) while ‘Evie 2’ has performed well in northern hydroponic trials (Wortman et al., 2016).

The United States is the largest producer of strawberries in the world with the largest production being warm weather states, such as California and Florida (Morgan, 2015). As consumer demand continues to grow so does the opportunity for controlled climate strawberry production (ERS, 2016). It is estimated that increased offseason production could expand the US strawberry industry by $520 M annually (Arnade and Kuchler, 2015).

The majority of strawberries are field-grown, although recently high tunnels are being used for production, particularly in coastal areas of California and to extend the season in cooler climates (Poppe et al., 2016; Pritts and Mcdermott, 2017). Hydroponic strawberry production has been found to have comparable yields to field production (Wortman et al., 2016) and hydroponic strawberry runner production (production of bare-root strawberry plants) has been proven as effective as field production (Takeda and Hokanson, 2003). Using aquaponic systems to grow strawberries has not been investigated to the best of our knowledge. There has been speculation that using aquaponic growing methods could be used to produce strawberry runners (Mattner et al., 2017) but no proof of concept has been attempted.

Adequate nutrient levels are critical for strawberry fruit maturation and achieving market fruit sizes. The recommended liquid fertilizer for strawberry irrigation in hydroponic nutrient solutions has a reduced nitrate concentration, less than half that of recommended tomato nutrient solution. Increased nitrate levels leads to tip-burn in strawberries and decreased production (*Cold Climate Strawberry Farming*, 2014). A short-term experiment examining nutrient levels in aquaponic strawberry production found that nutrient levels were adequate for growth but varied greatly depending on fish species and density (Villarroel et al., 2011). When production between a fully synthetic nutrient source, such as used in hydroponic systems and a bio-based liquid nutrient source (similar to aquaponic systems) were compared, strawberries grown with the synthetic nutrient source had 15% higher yield (Wortman et al., 2016).

Year-round aquaponic production studies have focused on the most popular aquaponic crops, leafy greens and herbs (Love et al., 2014). There has been limited research on year-round production of perennial crops, such as strawberries, in aquaponic production particularly in northern latitudes. The objective of this study is to produce day-neutral strawberries in year-round aquaponic production systems in northern latitudes to create a baseline for potential yield. The hypotheses tested in this experiment include: H_o: There is no difference in yield between strawberries produced aquaponically and those grown in soilless medium. Furthermore, there is no difference in yield between strawberries grown with different aquaponic treatments.

Materials and Methods

Genotypes Tested.

This experiment was conducted for a 13 month period (January 2016-February 2017). Three cultivars of day neutral strawberry plants were used for this experiment: ‘Portola’, ‘Albion’, and ‘Evie 2’, based on previous recommendations (Wortman et al., 2016; Petran et al., 2017). Cultivars were chosen based on previous winter cultivation studies (Paparozzi et al., 2010; Petran et al., 2017) and availability. Plants were acquired as pre-chilled, bare root transplants from Nourse Farms (South Deerfield, MA) and were received in week 55 (2015). The plants were held in a cooler at 3-5°C (darkness) until planting in each system tested. Bare-root plants were planted into each system in week 4

(2016). The location for aquaponics research was in the Minneapolis – Saint Paul Metropolitan area, State of Minnesota, U.S.A., specifically located at the St. Paul Campus of the University of Minnesota (44°59’17.8” N, -93°10’51.6” W).

Fish species grown in the various aquaponic production facilities were: *Perca flavescens* (yellow perch), *Oreochromis spp*. (tilapia), *Cyprinus carpio* (koi) and *Carassius auratus* (goldfish). The goldfish were purchased at PetSmart (Roseville, MN) in 2014. The tilapia were obtained as fingerlings from Arrowhead Fisheries, LLC (Canon City, CO) in January, 2015. Yellow perch were obtained as fingerlings from Will Allen Farms, Growing Power (Milwaukee, WI) in March 2015. Koi were obtained from Tangletown Gardens (Plato, MN) in February 2016. All fish were acclimated to each system’s environment, and then placed into each system as soon as biofilters were functioning.

Experimental Setup.

Environmental systems (treatments) tested included: (a) soilless medium (control), (b) floating raft deepwater culture (DWC), (c) A-frame ebb and flow, (d) tray ebb and flow, and (e) warehouse. Treatments (a) through (d) were conducted in greenhouses while (e) was in a warehouse. Treatments (c) and (e) used koi, treatment (b) used yellow perch, and treatment (d) used both goldfish and tilapia. All treatments had an equal number of each strawberry cultivars randomized throughout each system. All treatments except (c) used a randomized block design. Treatment (c) was randomized by PVC pipe line of plants (see Figure 1). The number of experimental units varied by treatment, the exact number depending on the space available in each system. In the soilless medium treatment, 32 plants/cultivar were grown; the A-frame ebb and flow had 8 plants/tube for a total of 48 plants/A-frame; the tray ebb and flow had 9 plants/tub; the floating raft DWC systems had 4 plants/tank whereas the warehouse had 30 plants/cultivar equally divided between the two growing tubs. In all systems strawberry plants were grown alongside basil (*Ocimum basilicum*) cultivars ‘Eleonora’, ‘Nufar’, and ‘Genovese’, and lettuce *(Lactuca sativa*) cultivars ‘Rex Butterhead’, ‘Salanova Sweet’ and ‘Salanova Incised’. Lettuce and basil production will be analyzed in a separate paper.

Environmental Conditions.

Soilless Medium (Control). The greenhouse environmental conditions for soilless medium strawberry production were 24.4±3.0/18.3±1.5°C day/night daily integral and a 16 hr long day photoperiod (0600–2200 HR) lighting (400 w high pressure sodium high intensity discharge lamps, HPS-HID) at a minimum of 150 µmol m^{-2} s^{-1}. The greenhouse, located in the St. Paul campus Plant Growth Facilities (University of Minnesota, St. Paul, MN), was an A-frame even-span construction, sharing one inner wall with each adjacent house. The roof, shared inner and interior walls adjoining the service walkway were glazed with double-strength float glass whereas the exterior walls had chambered acrylic (Exolite®; Cyro Industries, Mt. Arlington, NJ) glazing. Heating was delivered from the University of Minnesota heating plant via hot water into the perimeter pipes of the greenhouse with galvanized fins for enhanced heat exchange. All environmental settings were controlled via an Argus Control Systems Ltd. computer (Surrey, British Columbia, Canada).

Strawberries were transplanted into square 754 cm^3 plastic pots (Landmark Plastic, Akron, Ohio) filled with Sunshine LC8 soilless potting medium (Sun Gro Horticulture, Agawam, MA). Plants were fertilized twice daily, between the hours of 0700-0800 and 1600-1700, using a constant liquid feed (CLF) of 125 ppm N from water-soluble 20N–4.4P–16.6K (Scotts, Marysville, OH). Fungicide drenches of Banrot (Scotts, Marysville, OH), Subdue (Syngenta, Basel, Switzerland), Medallion (Syngenta, Basel, Switzerland), and Clearys 3336 (Nufarm, Melbourne, Australia) were applied in monthly rotations.

Insect control consisted of bio control methods of using yellow sticky cards (12.7 x 7.6 cm; Evergreen Growers Supply, Clackamas, OR) to catch flying insects. Additionally, a variety of mites, *Amblyseius andersoni*, *Amblyseius cucumeris, Amblyseius swirskii, Neoseiulus fallacis, Galendromus occidentalis, Neoseiulus californicus, Phytoseiulus persimilis* (Beneficial Insectary, Redding, CA and Rincon Vitova, Ventura, CA), were released rotationally for bio control in this and all other greenhouses and warehouse over the course of the experiment in order to control for spider-mites (*Tetranychus urticae*), white flies (*Trialeuroides vaporariorum*), and thrips (*Thysanoptera* spp.). Cease fungicide (Bioworks Inc., Victor, NY) was applied weekly during November 2016 in order to control for powdery mildew (*Podosphaera xanthii*).

Floating Rafts. This aquaponic greenhouse had a $23.6\underline{+}0.8$°C daily integral; the temperature set-point was 23.5°C. The same photoperiod (long day) and biocontrol methods, as instituted in the soilless medium treatment were also used herein. Electric generators served as the electrical power backup system for this and all other aquaponic setups.

This system consisted of eight aluminum tanks (193x77.5x75 cm, l x w x h with 6.5 cm thick walls) for fish/plant production. Each tank had a floating raft system (2/tank; 60x60x5.5 cm, Owens Corning FOAMULAR 150, R-10 insulation sheathing; Owens Corning Co., Toledo, OH); the water volume in each tank was ~550 L or 0.55 m3. Two plastic, hemispherical tanks (68x47x26 cm) were connected to each fish tank and served as the biofilters. Each biofilter was filled with 8-10 cm dia. gravel (D-Rock Center, New Brighton, MN). In greenhouse 369-C2, ammonium chloride (1 g/biofilter; Hawkins Chemical Co., Roseville, MN) was used to start the biological filter or biofilter in 8-10 cm dia. lava rock (D-Rock Center, New Brighton, MN) to produce ~1 mg/L ammonia with an initial start of *Carassius auratus* (goldfish) whereas ammonium carbonate was used in 369-C4. Two plastic, hemi cylindrical tanks (68x47x26 cm) were mounted above one end of each fish tank and served as the biofilters. Each biofilter was filled with 2 cm dia. granite gravel (Hedberg Aggregates, Stillwater, MN). A low density (approx. 25-30 fish / tank) of *Carassius auratus* was used to start the biological filter in the gravel; these were later removed before the experiment commenced and replaced with *Perca flavescens* (yellow perch). Water was lifted to the biofilter tanks by a Danner Supreme 700 GPH mag drive pump. The outflow was had valves and was split between the two biofilter tanks and a third outlet which discharged directly to the fish tank for added aeration and circulation. Each biofilter received approximately 4 l/min. An automatic bell siphon in each of the biofilter tanks allowed the water level to rise in the gravel from a low point of approximately 2 cm depth to a high of around 15 cm. At the high point the siphon would start and the water would draw down (returning to the fish tank), creating an ebb and flow in the gravel. Potential plant spacing on each raft could be a max. of 16 plants in a 4x4 grid, each plant could be grown in a 12cm dia. Net Cup (Hydrofarm Central, Grand Prairie, TX) filled with Trock rockwool (medium grade, 4CF, 30/PL; Therm-O-Rock East, Inc., New Eagle, PA).

Water quality was monitored daily (5/wk excluding weekends). Temperature measurements averaged 22.3+0.9°C and closely approximated the air temperature set point. The fish species grown in this house and used for the duration of the experiment was *Perca flavescens* (yellow perch) at varying densities (from 20-30 fish), depending on age (Sorensen et al., 2015). The same biocontrol methods for insect and arachnid pest control were instituted in this and all other greenhouses, as delineated earlier.

A-frame ebb and flow. In this greenhouse, 21.7±0.4°C was the daily integral and the temperature set-point was 21.5°C. Temperature measurements averaged 23.5±0.9°C and approximated the air temperature set point. The same photoperiod (long days) and bio control methods, as instituted in the soilless medium treatment, were also used herein.

Two tanks in this greenhouse each feed separate A-frame ebb and flow systems (Figure 1). Fish species grown in this house were *Cyprinus carpio* (koi) at varying densities, depending on fish age. Airlift pumps move the water from the fish tank to the biofilter; a Danner Supreme 700 GPH mag drive pump lifts the water from the biofilter to the A-frame lines, draining back to the fish tank. Four plastic, hemi cylindrical tanks

(68x47x26 cm) were mounted below each A-frame were filled with 3-4 cm dia. lava rock (D-Rock Center, New Brighton, MN) and served as the biofilters.

Tray ebb and flow. In this greenhouse, 21.7±0.4°C was the daily integral and the temperature set-point was 21.5°C. The same photoperiod (long days) and bio control methods, as instituted in the soilless medium treatment, were used in this greenhouse.

One fish tank (aluminum; identical specifications as used in the floating raft and A-frame ebb and flow systems) is used for each separate galvanized steel framed, adjustable shelving rack system (Ebb and Flow systems). One fish tank contained *Oreochromis spp*. (tilapia), which fed one shelving rack system, while *Carassius auratus* (goldfish) were grown in the other tank. All fish were at varying densities, depending on fish age.

Each system has two shelves/rack (Figure 2). Two tubs/shelf (123x94x18 cm; Polytank Co., Litchfield, MN), each of which could hold six 50.8x25.4 cm (10”x20”) trays into which separate plug trays (50s or 72s) were inserted to hold the plants. The top shelf of each rack system is exposed to natural and supplemental lighting (high pressure sodium HID lights) whereas the second shelf has supplemental light emitting diode (LED) lighting supplied by either Sunshine Systems GrowPan (450-470, 630 nm; 300 Watt; Sunshine Systems, LLC, Wheeling, IL) or Green Power LED (450-470, 660 nm; 300 Watt; 152x12 cm; 110v strips; Royal Philips N.V., Andover, MA). One plastic, rectangular tub (123x186x18 cm; Polytank Co., Litchfield, MN) serves as a biofilter for each tank and is filled with 3-4 cm dia. lava rock (D-Rock Center, New Brighton, MN). Each tub is located on the concrete floor.

Warehouse. The warehouse system is a retrofitted walk-in cooler (7.19m x 4.87m x 2.74m), in the basement of the plant growth facilities head house, with galvanized interior walls where a F5 (Fantastically Fun Fresh Food Factory) commercial type systems from Nelson and Pade Company (http://aquaponics.com/; Montello, WI) is installed. The F5 system consists of one 110-gallon fish tank with separate bio filters and 2—3' x 5' plastic tubs that will hold floating rafts. There are 15 - 2" net pots / raft and 2 rafts/tub for a total of 90 plants possible to be grown in this system. The LED lighting system from Agrivolution LLC (http://www.agrivolution.co/; South Windsor, CT) is a triple-band LED light (bar) above the plants, which can telescope vertically, depending on the plant height. The LEDs have single-chip diodes emitting blue, green, and red light with full photosynthetically active radiation (PAR=400 nm to 700 nm). Supplemental cooling is supplied to maintain average growing temperatures of 20-21°C day/night.

Fruit was harvested as it became ripe (fully red); dates of harvest were recorded. Berries were grouped by plant, counted, weighed (fresh weights, g), recorded, and then placed in a high temperature oven (76.67°C) (Hotpack, Philadelphia, PA) for seven days. Berries were then removed and weighed once more after drying was complete (dry weights, g). Average fresh berry weights were calculated as (average total fresh berry weight divided by the average berry number).

Statistical Analyses.

A Kruskal-Wallis test was used to analyze number of fruit per plant per harvest, weight in grams of fresh fruit per plant per harvest, and dry weight in grams of fruit per plant per harvest. The Kruskal Wallis test is an appropriate statistical analysis when the purpose of research is to assess if a difference exist on one ordinal/continuous dependent variable by an independent variable with two or more discrete groups. The dependent variables in this analysis are number of fruit, fresh fruit weight, and dry fruit weight, and the discrete groups are growing conditions and cultivars.

The Kruskal-Wallis test is a non-parametric variation of a one-way repeated measures, unbalanced analysis of variance (ANOVA) and is used to determine if three or more samples come from the same distribution (Ostertagová et al., 2014). A Kruskal-Wallis test was conducted due to the large number of outliers in the data, which indicated a non-normal error distribution. Normality and homogeneity of variance are not assumed when conducting the Kruskal Wallis test. The Kruskal Wallis test can be done when the data is ordinal-level or when it violates the assumptions of the ANOVA. Scores simply must be independent of each other, and must be in one of the groups of the independent variable. All tests were conducted using the software SAS v.9.4 (Cary, North Carolina).

Results

The number of fruits per plant per harvest, fresh fruit weight by plant, and dry fruit weight by plant were all significant at $P \leq 0.01$ or greater (Table 1) when compared by greenhouse location (both ebb and flow systems resided in the same greenhouse). When berries from all treatments, both aquaponic and soilless medium, were compared by treatment there was a significant difference in fresh fruit weight and dry fruit weight but not in number of fruit per plant (Table 1). Fish treatment only, excluding soilless medium treatment data, had no significant difference across categories indicating the significant difference was between aquaponically grown and soilless medium grown, not the different aquaponic treatments. When cultivars were compared there was also a significant ($P \leq 0.01$ or greater) difference in the number of fruit per plant per harvest, fresh fruit weight, and dry fruit weight (Table 1).

Table 2 shows the average and standard deviation of number of fruit per plant per harvest, fresh fruit weight, and dry fruit weight subdivided by location and fish treatment, including the soilless medium. There was a large amount of variation within all treatments as evidenced by the large standard deviations (Table 2). The floating raft DWC, which had perch as the fish treatment, had the highest average fresh fruit weight at 25.56 grams. The soilless medium treatment had the lowest fresh fruit weight with 18.11 grams. Though dry fruit average weight soilless medium treatment had the highest average weight with 2.05 grams, while the tray ebb and flow goldfish treatment and the ebb and flow A-frame treatment had the lowest average dry weight with 1.31 grams. This indicates there was significantly more water content in aquaponically grown strawberries than those which had the soilless medium treatment.

There was a significant difference among strawberry cultivars for all measured factors. ‘Evie 2’ produced a significantly higher number of berries per plant per harvest ($P \leq 0.01$; Table 3), averaging 4.37 berries, than both ‘Albion’ and ‘Portola’ with averages of 2.80 berries and 3.12 berries, respectively (Table 3). ‘Evie 2’ berries also had significantly ($P \leq 0.01$) higher fresh and dry weight than the other cultivars with an average fresh berry weight of 6.30g. ‘Albion’ had the lowest average fresh berry weight, 5.43g, and ‘Portola’ had an average fresh berry weight of 5.82g. Since ‘Evie 2’ produced the most berries and had the largest berries on average, it follows that it also had the highest total fresh and dry fruit weight per harvest (Table 3). It is interesting to note, however, that though ‘Albion’ had the lowest average fruit count and lowest average fresh fruit weight, ‘Portola’ had the lowest dry fruit weight. This indicates that ‘Albion’ has a higher mass to water ratio.

Though plants were put into the system in January 2016, the first harvest did not occur until April 2016 – the time required for leaf unfolding, flowering and fruit set. Harvests varied by month and by cultivar (Table 4), as is typical of day neutral strawberries (Rowley et al., 2011). The highest number of fruit for ‘Albion’ and ‘Evie 2’ was harvested in November 2016 (Table 4). However, the highest total fresh fruit weight was harvested in June for ‘Evie 2’ and July for ‘Albion’, indicating that berries produced in later months were smaller than those produced in the first large harvest. In general, average individual berry size trended downwards over time for all cultivars (Table 4).

Discussion and Conclusion

The average berry weight of this study is half as much for ‘Albion’ and less than half for ‘Evie 2’ than any other study examining strawberry production using alternative production methods (Table 5). The hydroponic study of Paparozzi et al. (2010), reported average berry sizes of 11.68g for ‘Albion’ and 16.31g for ‘Evie 2’, while the average fresh weight per berry in this study was 5.43g and 5.82g, respectively (Table 2).

The soilless medium treatment had the lowest average fresh berry weight at 18.1g, significantly less than the DWC floating raft treatment at 25.5g. However, it had the highest average dry berry weight with 2.04g, which was significantly more than the tray ebb and flow goldfish and the A-frame ebb and flow koi treatments at 1.30g. This suggests that berries grown in soilless medium have a higher mass to water ratio, which may impact taste and nutrition, though this study did not address those factors.

While ‘Albion’ had the lowest fresh berry weight and the lowest average number of fruit ‘Portola’ had the lowest dry fruit weight, this suggests ‘Albion’ has a higher mass to water ratio in the berries. This is consistent with previous research confirming ‘Albion’ has a higher Brix score (sugar content score) than other cultivars (Petran et al., 2017).

A study comparing differences between row covers in field strawberry production found average fresh berry weight of plasticulture row covers, typical of field production, to be 14.32g for ‘Albion’, 12.96g for ‘Evie 2’, and 14.78g for ‘Portola’ (Jordan, 2013). The same experiment evaluated strawberry cultivar production in low tunnel production systems and found average fresh fruit weight of ‘Albion’, ‘Evie 2’, ‘Portola’ to be 15.16g, 14.86g, and 18.61g, respectively (Jordan, 2013). A follow up study was conducted in 2017 using the same plasticulture row covers with average fresh berry weight of ‘Albion’ at 16.1g and ‘Portola’ at 18.1g (Jordan, 2017). A study measuring high tunnel strawberry production found the average berry size of ‘Albion’ to be 13.7g and ‘Evie 2’ to be 12.1g (Rowley et al., 2011). These results are consistent with other studies of field and low tunnel production using the chosen cultivars (*cf.* Table 5, Petran et al., 2017). All studies reported over double the average fresh berry weight found in this study.

A marketable berry is considered to be over 10g, completely and evenly red, and evenly filled without major deformities (Rowley et al., 2011). In terms of fresh weight we did not reach an average berry weight above 10g in any cultivar for any month (Table 4). Though we did not distinguish between marketable and unmarketable berries in this study, it is important to keep marketability in mind when considering the issues of strawberry production in aquaponic systems.

The reduced berry size in this study is not completely unexpected. Aquaponics has several known intrinsic issues like iron deficiency (Graber and Junge, 2009) which reduces photosynthesis and a lack of pollinators which directly affects fruit fill. All strawberry cultivars in all aquaponic systems had severe iron deficiency symptoms, due to insufficient levels of Fe in the aquaponic tanks. There are methods in development to overcome these issues but they were excluded in order to understand the potential yield of strawberry in aquaponic systems without supplemental inputs.

Iron deficiency has a significant negative impact on strawberry fruit production (Roosta, 2014). Strawberry iron uptake fluctuates over the life cycle of the plant increasing when vegetative growth occurs and decreasing during berry formation and ripening (Chow et al., 1992). Iron is a micronutrient used in the production of chlorophyll and in reproductive processes. It is the micronutrient needed in strawberries at highest quantities (Kobayashi and Nishizawa, 2012). Lack of iron in plants causes interveinal chlorosis or yellowing of the tissue in leaves. Symptoms continue to worsen until the leaf becomes completely white, leading to stunting of the plant and eventual death. Strawberries grown hydroponically are recommended to have 2.5g/L iron chelate included in the nutrient solution for ideal growth (de Villiers, 2008) although how effective plant uptake is depends on what kind of chelating agent is used and the pH of the system (Lucena et al., 1990).

To correct for iron chlorosis in hydroponic or field settings either a solution of chelated iron would be added directly to the roots or alkalinity would be lowered (pH =6.5). Keeping the pH <6.5 makes iron more soluble and able to be taken up by the plants. The other option, adding iron to the directly to the water of the aquaponic system, may have negative consequences on the fish or nitrifying bacteria in the biofilter. Fish tolerance of high iron levels is not known but probably varies by species (Kwong and Niyogi, 2008). Iron absorption in fish has been shown to be very inefficient (Bury and Grosell, 2003) which could indicate that addition of chelated iron to water in aquaponic systems is possible. A study done by Ru, et al. (2017) added 2mg/L Fe-EDTA weekly with positive effects to plant growth and no negative effects to the fish (Ru et al., 2017). Modifying the fish feed to include more iron may also increase availability in the system. Fish feeds range from 30 to 170mg iron Kg^{-1} (Watanabe et al., 1997).

Though strawberry roots can absorb iron more efficiently than any other part of the plant, the difficulties in getting chelated iron to them has led to the development of iron foliar sprays (Dordas, 2008). Iron foliar sprays can be effective in reversing chlorosis on strawberry (Pestana et al., 2011). Iron can also be absorbed through stomatal openings as it has been found that foliar applications to the underside of leaves are more effective than those applied to the top side (Schlegel et al., 2006). Aquaponic growers operating in greenhouses are suggested to apply iron foliar sprays in the morning in order to stimulate photosynthesis and maximize uptake (Brüggemann et al., 1993). Growers with fully artificial light are recommended to add a strong blue light to contribute to iron reduction and stomatal opening (Brüggemann et al., 1993).

There is also the threat of pests and diseases, which did not spare this study. Spider-mites (*Tetranychus urticae*) and powdery mildew (*Podosphaera* ×*anthii*) were issues for all cultivars, despite the bio control methods, especially in the greenhouse housing the A-frame ebb and flow and the tray ebb and flow systems. No strawberry cultivar showed any resistance to spider mites. Thus, there are multiple opportunities for day neutral strawberry breeders for cultivar improvement before greenhouse or warehouse aquaponic strawberry production can be viable.

Spider-mite infestation was an ongoing problem in greenhouse housing the A-frame ebb and flow and the tray ebb and flow systems and affected all treatments therein. Due to toxicity to the fish it was not possible to treat these with pesticides, as would be standard practice in regular greenhouse cultivation. Bio controls in the form of various species of mites, which are parasitic to spider mites, were regularly released. However, this bio control method takes 2-3 weeks to reduce populations of spider-mites and has to be continuously renewed (Pundt, 2014). Having a spider-mite infestation reduces day neutral strawberry yield by an average 23% (Walsh et al., 2002).

Powdery mildew was recognized on strawberry plants in the greenhouse housing the A-frame ebb and flow and the tray ebb and flow systems beginning in November 2016. It was treated using a biological fungicide spray once a week and was controlled within a month. Extensive infection can cause yield loss of up to 60% in strawberry (Asalf et al., 2012). Even when infection is not severe, powdery mildew can still cause yield loss of 5% when observed infection is less than 20% (Carisse et al., 2013). During the month of November 2016, total soilless media berry yield was 2324g while total berry yield for the greenhouse housing the A-frame ebb and flow and tray ebb and flow was 845g. This indicates there was substantial yield loss due to powdery mildew infection.

Pollinators were not added to any of the tested production systems, which may have had an impact on berry size. Berry fill in strawberries is determined by successful pollination and fertilization of the ovule which stimulates fruit fill (Nitsch, 1950). We relied on gravity and air movement to pollinate strawberry flowers which has been shown to have a pollination success rate of up to 60% (Vincent et al., 1990). The addition of pollinators to other greenhouse experiments has been shown to significantly increase berry size and weight (Abrol et al., 2017). Lower pollination success most likely contributed to smaller berry size throughout this experiment. Though we did not distinguish between marketable and non-marketable berries, the lack of insect pollinators has been shown to lead to uneven pollination and misshapen berries (Nye and Anderson, 1974).

If there had been sufficient plant accessible iron, adequate pollination, and had there not been a spider mite infestation, it is possible average berry size could have been over 10g. Iron foliar sprays to iron deficient plants have been shown to increase yield by up to 56% (Zaiter et al., 1993). Spider mite infestation reduces strawberry yield an average of 23% (Walsh et al., 2002). Finally, the lack of pollinators reduces fruit set and total yield by up to 4 fold (Abrol et al., 2017). It is reasonable that average berry size could have been comparable to field production methods if these essential strawberry production needs had been met.

There was a significant difference in cultivars in this study, specifically 'Evie 2' producing more significantly heavier berries (fresh weight) than the other cultivars (Table 3). 'Evie 2' has consistently performed better in controlled environments (Petran et al., 2017). It was among the highest yielding cultivars in hydroponic trials in the Midwest (Wortman et al., 2016). 'Evie 2' was bred to improve upon day neutral cultivars in northern climates with hot summers ("Evie 2 Plant Breeders Rights," 2018). Its improved tolerance to temperatures over 33^{o}C and moderate resistance to powdery mildew make it ideal for production in controlled environments. To further improve day neutral strawberries for aquaponic production in both greenhouses and warehouses, plant breeders should focus on increasing iron uptake or chlorosis resistance and resistance to spider mites while maintaining or increasing high fresh fruit yield and quality.

Strawberry production using aquaponic systems has many different issues that cannot be ignored if yield is to be equivalent to other systems. Though the number of berries per plant across systems is equivalent without supplemental inputs to the system, aquaponic strawberry fruit size is significantly lower than both field and hydroponic cultivation methods. Adding iron and pollinators, as well as controlling for pests and disease should increase aquaponic production. Choosing a cultivar such as ‘Evie 2’ that is suited to indoor production will make a significant difference in yield, unlike choosing between the different species of fish. Further research should focus on breeding of new strawberry cultivars better suited to aquaponic growing conditions and standardization of recommendations regarding inputs into aquaponic systems for supplemental iron treatments.

Table 2-1: Significance levels of fruit count, fresh fruit weight (g) by plant, and dry fruit weight (g) by plant of strawberries grown for treatment comparisons.

Treatment Comparisons	Fruit Count	Fresh Fruit Weight (g) by	Dry Fruit Weight (g) by Plant
Aquaponic Locations by Greenhouse	0.0020**^{z}	0.0067**	$\leq$0.0001**
Fish, Soilless Medium Included	0.0990ns	0.0061**	$\leq$0.0001**
Fish without Soilless Medium Included	0.1904ns	0.1832ns	0.0708ns
Cultivar	$\leq$0.0001**	$\leq$0.0001**	$\leq$0.0001**

^{z} ns, ** indicates not significant and $P \leq 0.01$, respectively.

Table 2-2: Mean and standard deviation of fruit count by plant per harvest, fresh fruit weight, and dry fruit weight of day neutral strawberries grown in soilless medium as well as aquaponic greenhouse and warehouse treatments and four fish types.

Measurement	Treatment	Fish types	Mean	Standard Deviation
Fruit Count per Plant	Soilless medium	-	3.22a^z	2.31
	Floating raft DWC	Perch	3.88 a	3.03
	Tray ebb and flow	Goldfish	3.11 a	2.29
	A-frame ebb and flow	Koi	3.90 a	3.12
	Tray ebb and flow	Tilapia	3.57 a	2.85
	Warehouse	Koi	2.43 a	1.87
Fresh Fruit Weight (g) per Plant**	Soilless medium	-	18.1b	12.7
	Floating raft DWC	Perch	25.5 a	20.6
	Tray ebb and flow	Goldfish	19.3 ab	17.6
	A-frame ebb and flow	Koi	21.6 ab	17.1
	Tray ebb and flow	Tilapia	20.9 ab	17.9
	Warehouse	Koi	18.5 ab	12.4
Dry Fruit Weight (g) per Plant**	Soilless medium	-	2.04 a	1.40
	Floating raft DWC	Perch	1.67 ab	1.47
	Tray ebb and flow	Goldfish	1.30 b	1.10
	A-frame ebb and flow	Koi	1.30 b	1.07
	Tray ebb and flow	Tilapia	1.53 ab	1.21

Warehouse	Koi	1.54 ab	1.18

[z] Any two means within a column not followed by the same letter are significantly different at $P \leq 0.001$

Table 2-3: Mean and standard deviation of fruit count by plant per harvest, fresh fruit weight, and dry fruit weight of day neutral strawberry cultivars ‘Albion’, ‘Evie 2’, and ‘Portola’.

Measurement	Cultivar	Mean	Standard Deviation
Fruit Count per Plant**	‘Albion’	2.80 b	2.27
	‘Evie 2’	4.37 a	3.14
	‘Portola’	3.12 b	2.38
Fresh Fruit Weight (g) per Plant**	‘Albion’	15.2 b	11.1
	‘Evie 2’	25.4 a	20.0
	‘Portola’	19.7 ab	14.6
Dry Fruit Weight (g) per Plant**	‘Albion’	1.62 a	1.35
	‘Evie 2’	1.79 a	1.36
	‘Portola’	1.33 b	1.02

[z] Any two means within a column not followed by the same letter are significantly different at P≤0.001

Table 2-4: Amount by month from April 2016 to February 2017 and total number of fruit, fresh fruit weight (g), and individual fresh fruit weight (g) for all aquaponic treatments and soilless medium treatment of the day neutral strawberry cultivars ‘Albion’, ‘Evie 2’, and ‘Portola’.

Measurement	Month	‘Albion’	‘Evie 2’	‘Portola’	Grand Total
Fruit Count	April 2016	92.0	361.0	305.0	758.0
	June 2016	70.0	452.0	139.0	661.0
	July 2016	223.0	368.0	168.0	759.0
	August 2016	128.0	341.0	105.0	574.0
	October 2016	64.0	72.0	29.0	165.0
	November 2016	320.0	631.0	229.0	1180.0
	December 2016	107.0	109.0	61.0	277.0
	January 2017	63.0	119.0	106.0	288.0
	February 2017	5.0	4.0	8.0	17.0
	Grand Total	1072.0	2457.0	1150.0	4679.0
Fresh Fruit Weight (g)	April 2016	473.48	2567.63	1894.31	4935.42
	June 2016	471.73	3067.68	903.29	4442.7
	July 2016	1369.28	2234.99	1114.57	4718.84
	August 2016	645.08	1323.59	620.47	2589.14
	October 2016	378.76	438.56	252.93	1070.25

	November 2016	1126.36	1768.94	910.9	3806.2
	December 2016	550.7	610.8	489.2	1650.7
	January 2017	37.53	168.85	288.43	494.81
	February 2017	47.11	26.77	81.23	155.11
	Grand Total	5100.03	12207.81	6555.33	23863.17
Average Individual Fresh Fruit Weight (g) per Month	April 2016	5.15	7.11	6.21	
	June 2016	6.74	6.79	6.50	
	July 2016	6.14	6.07	6.63	
	August 2016	5.04	3.88	5.91	
	October 2016	5.92	6.09	8.72	
	November 2016	3.52	2.80	3.98	
	December 2016	5.15	5.60	8.02	
	January 2017	0.60	1.42	2.72	

Table 2-5: Reported average berry size for the day neutral cultivars ‘Albion’, ‘Evie 2’, and ‘Portola’ using aquaponic (all treatments), hydroponic, low tunnel, high tunnel, and field production methods.

Cultivar	Aquaponic	Hydroponic	Low Tunnel	High Tunnel	Field	Citations
‘Albion’	5.43g	10.81-11.68g	15.16g	13.7g	13.9-16.1g	Moore et al. 2013; Jordan 2017, 2013; Rowley et al. 2011; Paparozzi et al. 2010; Miranda et al. 2014
‘Evie 2’	6.3g	16.31g	14.86g	12.1g	12.92g	Jordan 2013; Rowley et al. 2011; Paparozzi et al. 2010
‘Portola’	5.82g	-	18.61g	-	14.78-18.1g	Jordan 2013, 2017

Figure 2-1: Diagram of the A-frame ebb and flow system showing the location of supplemental lighting, biofilter, fish tank, and plant lines with arrows indicating direction of water flow.

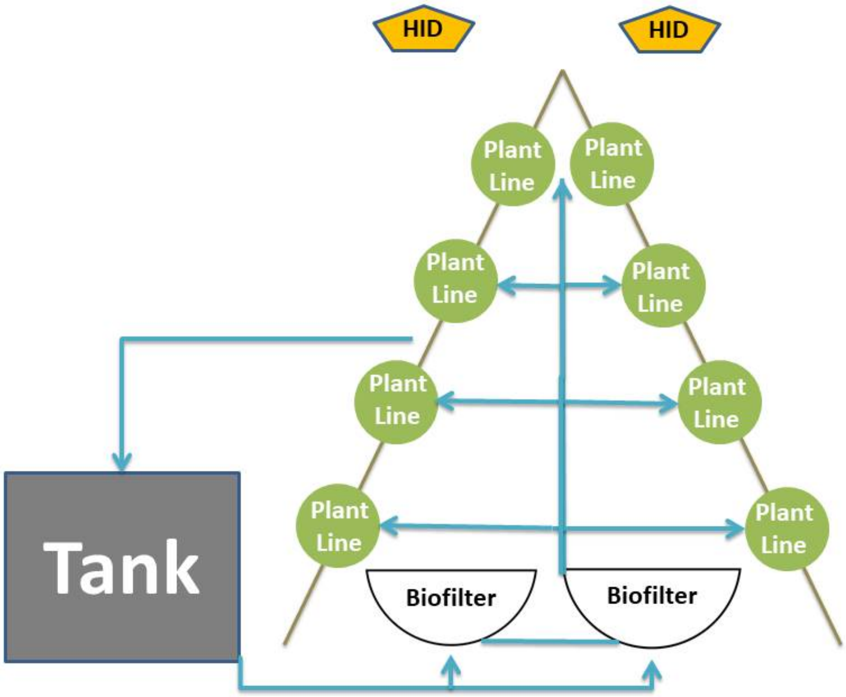
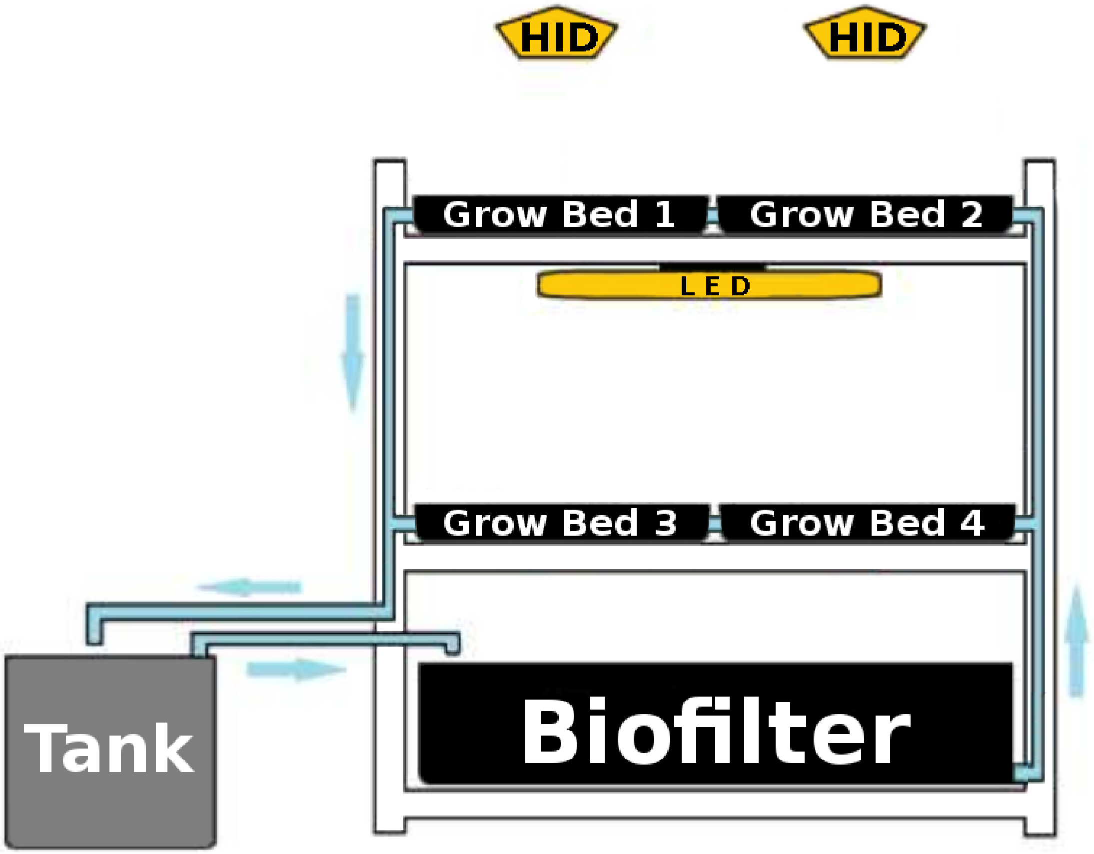


Figure 2-2: Diagram of the tray ebb and flow system showing the location of the supplemental light sources, grow beds, biofilter, and fish tank. Arrows indicate the direction of water flow. Figure modified from Gebhardt, et al. (2015).



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