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

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Abstract

Aquaponics, the combination of hydroponics and aquaculture into one growing system, is a controlled environment production system that potentially has increased environmental and consumer benefits over traditional production methods. 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 fruit crop. This study 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 had a higher mass to water ratio, although aquaponic-grown strawberries sometimes had higher fresh weight yield.

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 after processing through a biofilter while the plants provide a natural "filter" utilizing the resulting nitrate N and other nutrients (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

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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 depends 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 (*Fragaria ×ananassa*, Rosaceae) are an herbaceous, perennial crop that grow relatively close to the ground (maximum 30cm tall) and spread both sexually by seed and vegetatively via stolons (Vincent et al., 1990). Flowers grow in clusters on individual stalks 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) to initiate flower buds, ever-bearing (remontant) types need long day lengths (>12 hr) to initiate flower buds, and day-neutral cultivars are not affected by day length. There is also a temperature effect on flowering response. Bradford et al. (2010) found that non-remontant flowering 'Honeoye' had a photoperiod-insensitive temperature range of 14-20 °C whereas remontant types had a higher range of 23-26 °C. Whenever temperatures surpassed this range, genotypes required either short or long days to flower regardless of remontancy. 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, remontant 'Portola' and 'Albion' strawberries 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 in California and Florida (Morgan, 2015). As consumer demand continues to grow so does the opportunity for controlled climate strawberry production (USDA Economic Researh Service, 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 had comparable yields to field production (Wortman et al., 2016) and hydroponic strawberry runner production (production of bare-root strawberry plants) was 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 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 low 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). In a short-term experiment examining nutrient levels in aquaponic strawberry production 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 was 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: Ho: There is no difference in yield between strawberries produced aquaponically and those grown in soilless medium. Furthermore, Ho: 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 (Jan. 2016-Feb. 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), 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 experiment was conducted at the St. Paul Campus of the University of Minnesota Plant Growth Facilities (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. Tilapia were obtained as fingerlings from Arrowhead Fisheries, LLC (Canon City, CO) in Jan. 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 Feb. 2016. All fish were acclimated to each system's environment and then placed into each system as soon as the biofilters were functioning.

Experimental Setup.

Environmental systems tested included: (a) soilless medium (control), (b) floating raft deep-water culture (DWC), (c) A-frame ebb and flow, (d) tray ebb and flow, and (e) warehouse. Systems (a) through (d) were located in greenhouses while (e) was in a warehouse. Systems (c) and (e) used koi, treatment (b) used yellow perch, and treatment (d) used both goldfish and tilapia. Fish types were the treatments while strawberry cultivars were the variable; all treatments had an equal number of plants for each strawberry cultivar randomized throughout each system. All systems except (c) used a randomized block design. System (c) was randomized by PVC pipeline 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, 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.

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 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} PAR. The greenhouse, located in the St. Paul campus Plant Growth Facilities (University of Minnesota, St. Paul, MN), was an A-frame evenspan construction, sharing one inner wall with each adjacent house. The roof, shared

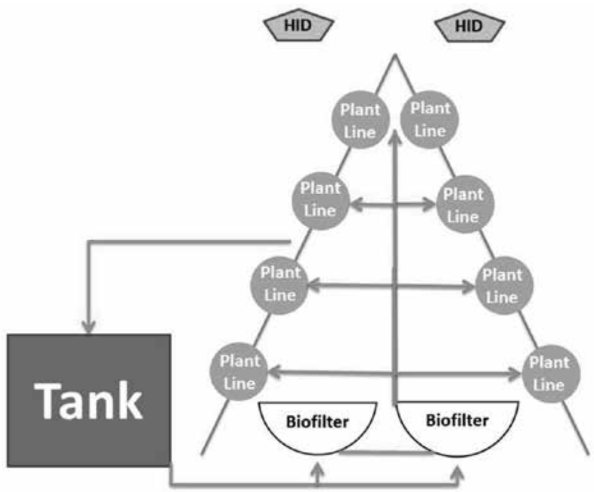

Figure 1. Diagram of the A-frame ebb and flow system showing the location of supplemental lighting, biofilter, fish tank, and plant lines with arrows indicating direction of water flow.

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, A. cucumeris, A. swirskii, Neoseiulus fallacis, Galendromus occidentalis, N. 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 Nov. 2016 to control powdery mildew *(Podosphaera xanthii)*.

Floating Rafts. This aquaponic greenhouse had a 23.6+0.8°C daily integral; the temperature set point was 23.5°C. The same photoperiod (long day) and bio control 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 m^3. 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 T-rock 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 bio control methods for insect and arachnid pest control were instituted in this and all other greenhouses, as delineated earlier.

<u>A-frame ebb and flow</u>. 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 moved 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.

<u>Tray ebb and flow</u>. 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) was 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 had 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 was 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 Grow Pan (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 was 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) was installed. The F5 system consisted of one 110-gallon fish tank with separate bio filters and 2—3' x 5' plastic tubs that hold floating rafts. There were 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

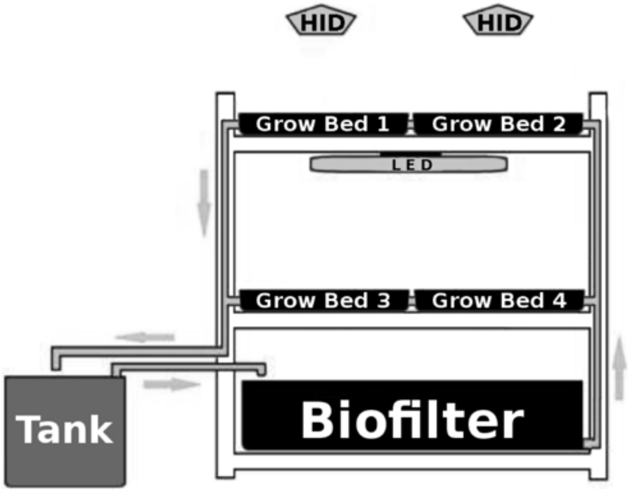

Figure 2. Tray ebb and flow aquaponic system setup showing the location of the supplemental light sources, grow beds, biofilter, and fish tank. Arrows indicate the direction of water flow. Figure modified from Gebhardt, et al. (2015).

LLC (http://www.agrivolution.co/; South Windsor, CT) was a triple-band LED light (bar) above the plants, which could telescope vertically, depending on the plant height. The LEDs had single-chip diodes emitting blue, green, and red light with full photosynthetically active radiation (PAR=400 nm to 700 nm). Supplemental cooling was supplied to maintain average growing temperatures of 20-21°C day/night.

Data Collection. Fruit was harvested when ripened (fully red); dates of harvest were recorded. Fruit were grouped by plant, counted (fruit count), weighed (fresh fruit weights, g), and then placed in a high temperature oven (76.67°C) (Hotpack, Philadelphia, PA) for seven days. Fruit were then removed and weighed after drying was complete (dry fruit weights, g). Average fresh or dry fruit weights (g) per plant were calculated as: average total fresh or dry weight / average fruit number.

Statistical Analyses. A Generalized Linear Mixed Model test using non-normal distribution (GLIMMIX) 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 analysis was conducted using a split-plot design with the type of fish as the treatment and the cultivar as the variable. The systems and fish are interchangeable as treatments to the split-plot design in this case because the cultivars were evenly and randomly distributed no matter whether 'fish' or 'system' is used as a treatment. Using 'fish' lowers the sample size, specifically in the case of the tray system of C4 going from both tilapia and goldfish included in one to them being separated but there were still equal numbers of cultivars randomly placed into each tray system. Thus, it still meets the requirements of a split plot design.

The koi treatments in system C and E were analyzed separately. Dependent variables in this analysis are the number of fruit, fresh fruit weight, and dry fruit weight.

The GLIMMIX determines the correlation between data that has been fit to a specified statistical model. Common non-normal distribution models were tested and the lognormal distribution was found to have the lowest AIC and BIC and, therefore, the best fit. GLIMMIX assumes a normal distribution of

Table 1. Significance levels of fruit count, fresh fruit weight (g) by plant, and dry fruit weight (g) by cultivar in treatment comparisons.

Treatment comparisons	Fruit count	Fresh fruit weight (g) by plant	Dry fruit weight (g) by plant
Systems A-E	.449 [z] ns	.923 [z]	.085*
Fish with soilless medium	.517 [z]	.883 [z]	.072*
Fish without soilless medium included	.445 [z]	.861 [z]	.468 [z]

[z] ns, *indicates not significant and $P \leq 0.10$, respectively.

random effects, which this experiment has. All tests were conducted using the software SAS v.9.4 (Cary, North Carolina).

Results

System (systems A-E) and fish with soilless medium significantly (P<0.10) affected dry fruit weight per plant, but not number of fruit or the fresh fruit weight per plant (Table 1). When data for soilless medium treatment were excluded from the analysis, dry fruit weight was affected by fish treatment, indicating that differences in dry fruit weight were likely due to differences between aquaponically-grown and soilless-medium-grown treatments.

Tables 2-4 show the average number of fruit per plant, fresh fruit weight, and dry fruit weight along with the standard deviation for each cultivar per system treatment and fish type, including the soilless medium. Variation was high within all treatments as evidenced by the large standard deviations (Tables 2-4). 'Evie 2' in the A-frame ebb and flow (Koi fish type) had the highest mean fruit count (5.30), followed by the floating raft DWC (perch, 4.66) (Table 2). Of the three cultivars, 'Evie 2' had the highest yield across all treatments and fish types, with the exception of the warehouse (Koi) where 'Portola' was the highest (Table 2). 'Evie 2' in the floating raft DWC, which had perch as the

Table 2. Means and standard deviations for fruit count per plant for three day neutral strawberry cultivars grown in soilless medium broken down by treatment, fish type, and cultivar.

Treatment	Fish types	Cultivar	Mean	Standard deviation
Soilless medium	-	Albion	2.98	2.22
		Portola	2.72	1.79
		Evie 2	3.90	2.63
Floating raft DWC	Perch	Albion	2.87	1.98
		Portola	3.20	2.45
		Evie 2	4.66	3.47
Tray ebb and flow	Goldfish	Albion	2.91	1.91
		Portola	2.69	2.42
		Evie 2	3.46	2.76
A-frame ebb and flow	Koi	Albion	2.59	2.69
		Portola	3.42	2.73
		Evie 2	5.30	4.17
Tray ebb and flow	Tilapia	Albion	2.64	2.08
		Portola	3.54	3.67
		Evie 2	4.09	3.20
Warehouse	Koi	Albion	1.00	0.00
		Portola	2.67	1.94
		Evie 2	2.1	2.07

Table 3. Means and standard deviations for fresh individual fruit weight (g) for three day neutral strawberry cultivars grown in soilless medium broken down by treatment, fish type, and cultivar.

Treatment	Fish types	Cultivar	Mean	Standard deviation
Soilless medium	-	Albion	16.15	11.11
		Portola	17.19	12.84
		Evie 2	21.02	13.97
Floating raft DWC	Perch	Albion	15.11	10.63
		Portola	21.96	14.93
		Evie 2	31.59	24.08
Tray ebb and flow	Goldfish	Albion	19.51	16.82
		Portola	16.83	19.98
		Evie 2	21.08	22.89
A-frame ebb and flow	Koi	Albion	13.66	11.32
		Portola	20.77	15.46
		Evie 2	26.49	19.13
Tray ebb and flow	Tilapia	Albion	11.99	10.25
		Portola	21.14	21.06
		Evie 2	27.76	28.32
Warehouse	Koi	Albion	11.55	4.35
		Portola	12.37	13.55
		Evie 2	14.89	10.89

Table 4. Means and standard deviations for dry individual fruit weight (g) for three day neutral strawberry cultivars grown in soilless medium broken down by treatment, fish type, and cultivar.

Treatment	Fish types	Cultivar	Mean	Standard deviation
Soilless medium	-	Albion	2.32	1.54
		Portola	1.54	1.10
		Evie 2	2.13	1.36
Floating raft DWC	Perch	Albion	1.16	10.63
		Portola	1.46	1.14
		Evie 2	1.99	1.72
Tray ebb and flow	Goldfish	Albion	1.47	1.13
		Portola	1.03	0.95
		Evie 2	1.25	1.16
A-frame ebb and flow	Koi	Albion	1.11	1.25
		Portola	1.04	0.87
		Evie 2	1.67	1.44
Tray ebb and flow	Tilapia	Albion	1.30	1.15
		Portola	1.41	1.24
		Evie 2	1.81	1.27
Warehouse	Koi	Albion	1.23	0.32
		Portola	1.90	1.46
		Evie 2	1.10	0.57

fish treatment, had the highest average fresh fruit weight (31.59 g, Table 3). For all treatments and fish types, 'Evie 2' had the highest average fresh fruit weights. 'Albion' in the warehouse system, with koi, had the lowest fresh fruit weight (11.55 g, Table 3). Average dry individual fruit weight was highest for 'Albion' in soilless medium treatment (2.32 g) whereas 'Portola' in the tray ebb and flow goldfish treatment and the ebb and flow A-frame treatment had the lowest average dry weight (1.03 and 1.04 g, respectively, Table 4). This indicates there was significantly more water content in aquaponically grown strawberries than those from the soilless medium treatment. 'Evie 2' had the highest average dry weight in only three treatments and fish types: floating raft DWC/perch, A-frame ebb and flow/Koi, and tray ebb and flow/Tilapia (Table 4).

Since 'Evie 2' produced the most fruit on average (Tables 2 and 3), it follows that it also had the highest total fresh fruit weight per harvest (Table 5). 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' had

Table 5. Fruit count by month (from April 2016 to February 2017), total number of fruit, fresh fruit weight (g), and individual fresh fruit weight (g) for three day neutral strawberry cultivars averaged over all aquaponic treatments and soilless medium treatment.

Measurement	Month	'Albion'	'Evie 2'	'Portola'	Totals
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
	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
	Total	5100.03	12207.81	6555.33	23863.17
Average individual fresh fruit weight (g) per month	April	5.15	7.11	6.21	
	June	6.74	6.79	6.50	
	July	6.14	6.07	6.63	
	August	5.04	3.88	5.91	
	October	5.92	6.09	8.72	
	November	3.52	2.80	3.98	
	December	5.15	5.60	8.02	
	January	0.60	1.42	2.72	

a higher mass to water ratio.

Though plants were put into the system in Jan. 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 5), as is typical of day neutral strawberries (Rowley et al., 2011). The highest number of fruit for 'Albion' and 'Portola' was harvested in Nov. 2016 whereas for 'Evie 2' the highest fruit count occurred in June 2016 (Table 5). However, the highest total fresh fruit weight was harvested in June for 'Evie 2' and July for 'Albion', although for 'Portola' this occurred even earlier in April 2016 (Table 5). This indicates that fruit produced in later months were smaller than those produced in the first large harvest period. In general, average individual fresh fruit weight (g) per month declined over time for all cultivars (Table 5).

Discussion

The average fruit weight in 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 6). The hydroponic study of Paparozzi, et al. (2010), reported average fruit sizes of 11.68g for 'Albion' and 16.31g for 'Evie 2' (Table 6), 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 fruit weight (18.1g), significantly less than the DWC floating raft treatment (25.5g). However, it had the highest average dry fruit weight (2.04g), which was significantly more than the tray ebb and flow goldfish and the A-frame ebb and flow koi treatments (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 fruit weight and the lowest average number of fruit, 'Portola' had the lowest dry fruit weight, suggesting 'Albion' has a higher mass to water ratio. This is consistent with previous research confirming 'Albion' had higher total soluble solid concentration than other cultivars (Petran et al., 2017).

In a study comparing differences between row covers in plasticulture field strawberry production, average fresh fruit weight was 14.32g for 'Albion', 12.96g for 'Evie 2', and 14.78g for 'Portola' (Jordan, 2013). For low tunnels in the same experiment, average fresh fruit weight of 'Albion', 'Evie 2', 'Portola' was 15.16g, 14.86g, and 18.61g, respectively (Jordan, 2013). A follow up study, conducted in 2017 using the same plasticulture row cov-

Table 6. Reported average fruit weight (g) for the day neutral strawberries 'Albion', 'Evie 2', and 'Portola' grown in aquaponic (all treatments), hydroponic, low tunnel, high tunnel, and field production systems.

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

ers, had average fresh fruit weight of 16.1g for 'Albion' and 18.1g for 'Portola' (Jordan, 2017). In a high tunnel experiment, average fruit size for 'Albion' was 13.7g while 'Evie 2' had 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 during 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.

Small fruit in this study was 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 fruit 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 leaves. Symptoms intensify 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 the effectiveness of plant uptake depends on the type of chelating agent 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 is 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 directly to the water of the aquaponic system, may have negative consequences on the fish and/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 subsequent to this study by Ru, et al. (2017) added 2mg/L Fe-EDTA weekly with positive effects to plant growth and no negative effects to the fish. Modifying the fish feed to include more iron may also increase availability in the system. Fish feeds range from 30 to 170mg iron per Kg (Watanabe et al., 1997).

While 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 the 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). Spider mite infestations reduce day neutral strawberry yield by an average 23% (Walsh et al., 2002).

Powdery mildew was observed on strawberry plants in the greenhouse housing the A-frame ebb and flow and the tray ebb and flow systems beginning in Nov. 2016. It was controlled within a month with weekly sprays of a biological fungicide. Extensive infection can cause yield losses of up to 60% in strawberry (Asalf et al., 2012). Even when infection is not severe, powdery mildew can still reduce yield by 5% when observed infection is less than 20% (Carisse et al., 2013). During the month of Nov. 2016, fruit yield in the total soilless media was 2324g and only 845g fruit for the greenhouse housing the A-frame ebb and flow and tray ebb and flow. 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 fruit size. Fruit 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 significantly increased fruit size and weight (Abrol et al., 2017). Poor pollination most likely contributed to small fruit size throughout this experiment. Though we did not distinguish between marketable and non-marketable fruit, the lack of insect pollinators led to uneven pollination and misshapen fruit (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 fruit size could have been over 10g. Iron foliar sprays to iron deficient plants increased 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 fruit 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’ produced more significantly heavier fruit (fresh weight) than the other cultivars (Table 3). ‘Evie 2’ consistently performed better in controlled environments (Petran et al., 2017) and 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 (Edward Vinson Limited, 2018). Its improved tolerance to temperatures over 33°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.

Conclusion

Strawberry production using aquaponic systems has many challenges that cannot be ignored if yield is to be equivalent to other systems. Though the number of fruit per plant across systems was equivalent without supplemental inputs to the system, aquaponic strawberry fruit size was significantly lower than both field and hydroponic cultivation methods. Adding iron, including pollinators, as well as controlling arthropods 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.

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