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Integrating Greenhouse Cherry Tomato Production with Biofloc Tilapia Production

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Received: 30 November 2019; Accepted: 30 July 2020; Published: 4 August 2020

Abstract: Integration of intensive aquaculture systems with greenhouse plant production has been shown to improve aquaculture water quality conditions and improve plant nutrient use efficiency. The majority of the focus of integrated systems has involved raft culture or true hydroponics. Little work has been done on soilless culture utilizing drip irrigation. This study investigates the feasibility of integrating biofloc Nile tilapia (Oreochromis niloticus) production with greenhouse cherry tomato production (Solanum lycopersicum var. cerasiforme). Nile tilapia (157 g/fish) were stocked at 40 fish/m³ and grown for 149 days. The cherry tomato cvs. “Favorita” and “Goldita” were grown with aquaculture effluent (AE) waste and compared to plants grown with conventional fertilizer (CF) in soilless culture. Plants were grown for 157 days. Few differences in yield occurred between treatments until fish harvest (117 DAT). Post fish harvest, there was an 18.4% difference in total yield between CF and AE at crop termination for “Favorita”. Differences in yield between AE and CF were observed for “Goldita” at fish harvest (117 DAT) and crop termination (157 DAT). Results from this study suggest the potential for successful integration of cherry tomato grown in a substrate-based system with AE from a tilapia biofloc production system.

Keywords: aquaponics; hydroponics; recirculating aquaculture system (RAS); decoupled aquaponics

1. Introduction

Feed can account for over 50% of production costs in an aquaculture system [1]. Consequently, it is important to effectively convert feed into sellable products. Fish are among the most efficiently cultured animals in regard to feed conversion, but there is still a considerable amount of wasted nutrients associated with fish [2,3]. Recirculating aquaculture systems (RASs) improve water and space utilization over traditional pond-based systems, but traditional RASs do little to improve the nutrient use efficiency (NUE) of a system.

Biofloc technology (BFT) is a form of RAS that does not use traditional biofilters. BFT relies on the constant mixing of suspended solids in the water column. Solids in suspension in BFT-cultured water provide a surface area for heterotrophic and autotrophic bacterial growth. Most BFTs are operated where nitrogenous waste is primarily handled through mineralization by utilizing heterotrophic bacteria. Nitrogenous waste (primarily ammonia) is assimilated into microbial protein, converting N into a nontoxic form [4,5]. This technique is enhanced by increasing the C:N ratio of food, adding highly available carbon sources, or by lowering the protein content in feed [6,7]. BFT improves the feed conversion ratio (FCR) over clearwater systems, which enhances NUE of the system [7]. The BFT
system contains high concentrations of settleable solids that include microbial flocs, uneaten feed, and fecal waste.

Hydroponic vegetable production lends itself to integration into RASs, improving NUE. The integration of RASs with hydroponic vegetable production is commonly referred to as aquaponics [8]. Aquaponic systems improve NUE, decrease water consumption, and improve water quality over conventional RASs [9–12]. Quillere et al. [13] reported that 60% of applied nitrogen was recovered, with 28% being assimilated into plant biomass and 31% being assimilated into fish biomass when fish production was integrated with hydroponic tomato (Solanum lycopersicum L) production.

Aquaponic research has primarily involved leafy greens [9–11,14,15] and tomato [16–20]. Savidov et al. [21] evaluated 24 different plant species grown in an aquaponic system, demonstrating the variety of crops that can be grown aquaponically.

Little research has addressed integrating drip-irrigated plant production systems used in the greenhouse vegetable industry, with RASs. Soiless systems utilize highly porous substrates, allowing growers to manipulate nutrients in the root zone with frequent short irrigation cycles. Clogging of the micro-orifices associated with microirrigation with fish waste is a concern with aquaponics. High concentrations of settleable solids associated with BFT have had limited research on its integration with substrate-based growing systems. The purpose of this research is to evaluate the integration of BFT aquaculture effluent (AE) as a nutrient solution for greenhouse cherry tomato using a substrate-based hydroponic system.

2. Materials and Methods

Facilities used in this research consisted of 2 commercial-size greenhouses located at the E.W. Shell Fisheries Center, North Auburn Unit, approximately 10 km north of Auburn, Alabama, USA (32.649171° N, −85.486725° E). The fish culture system was housed in a 267.6 m² double-polyethylene covered greenhouse (9.1 × 29.2 m) with an east to west orientation and consisted of 2 rectangular tanks (1.2 × 3 × 26.8 m), each with an average volume of 100 m³, operated as a biofloc system [5]. A 1.9 m³ cone-bottomed clarifier (30% slope), adjacent to the greenhouse, was used to reduce suspended solids concentration from the system (Figure 1). Water flowed through the clarifier at an approximate flow rate of 18.9 L·min⁻¹ and entered a 1.1 m³ cone-bottomed irrigation sump of a similar design before re-entering the fish production tank. Both vessels had an uninterrupted and constant flow of water, driven by airlift pumps. The clarifier and irrigation sump were flushed of collected solids twice daily.

The 267.5 m² (9.1 × 29.2 m) plant greenhouse was covered with double-layered polyethylene sheeting with a north to south orientation. The plant greenhouse was outfitted for soilless vine crop production, with a steel cable trellis system running the length of the greenhouse and cables suspended approximately 2.1 m above the greenhouse floor. Two cables were suspended above each row, approximately 0.1 m from the row center. Each row was 1.5 m apart, and the plant-growing containers were spaced 40.6 cm apart within rows. Both greenhouses were equipped with environmental controls for year-round production.

For the purposes of this study, the south-facing tank was stocked with 3000 Nile tilapia (Oreochromis niloticus; 157 g/fish), 40 fish/m³, on 29 August 2012. Fish were hand-fed a 36% protein floating feed, with 6.0% crude fat and 3.5% crude fiber (Cargill®, Franklinton, LA, USA), at 13% body weight/day twice daily (8:30 a.m. and 4:00 p.m.) for approximately 20 min. Calcium-hydroxide (Ca(OH)₂) was applied after each feeding to maintain a targeted pH of 6.8 to 7.0 [8]. Oxygen was supplied by two 1118.5 W (1.5 horsepower) regenerative blowers feeding the air-diffusing tubing that was suspended around the walls of the fish tank. Dissolved oxygen and temperature of the fish culture water were recorded twice daily (YSI 550A, YSI Inc., Yellow Springs, OH, USA). Fish were harvested 150 days after stocking (24 January 2013). The water for fish production was sourced from a reservoir that is fed by the surrounding watershed.

To evaluate the yields of tomatoes grown with AE against conventionally grown plants, a commercially available hydroponic fertilizer, Bag Culture Tomato Special 3-13-29, (3.0% N; 13.0% P;
29.0% K; 0.1% B, Cu, and Mn; 0.34% Fe; 5.4% Mg; 0.01% Mo; 11.0% S; 0.045% Zn; Total Grow™, Winnsboro, LA, USA) and greenhouse-grade calcium nitrate (15.5N-0P-0K) were used for the control treatment. Plants were irrigated and fertilized at rates following recommendations by Hanna [22] (Table 1). The irrigation water source for CF-grown plants was supplied by the local municipal water source. The cherry tomato (S. lycopersicum var. cerasiforme) cvs. Favorita and Goldita (Paramount Seeds, Stuart, FL, USA) were used. On 1 October 2012, 8-week-old tomato transplants were transplanted into 11 L Bato pots (Bato Plastics B.V. Zevenbergen, The Netherlands) filled with commercial grade perlite. Two tomatoes were planted in each pot, resulting in a plant density of 3.2 plants/m², and placed in the high wire trellis system previously described. Each pot served as a single experimental unit.

### Table 1. Fertilization schedule for greenhouse tomato production. 

| Week Following Transplanting | Days Following Seeding | Fertilizer Components | Times of Irrigation per Day | N ppm | K ppm |
|-----------------------------|------------------------|-----------------------|-----------------------------|-------|-------|
| 1                           | 35                     | 45                    | 3                           | 56    | 100   |
| 2                           | 42                     | 52                    | 4                           | 77    | 110   |
| 3                           | 49                     | 60                    | 5                           | 90    | 130   |
| 4                           | 56                     | 67                    | 6                           | 99    | 150   |
| 5                           | 63                     | 75                    | 7                           | 113   | 170   |
| 6                           | 70                     | 82                    | 8                           | 129   | 190   |
| 7                           | 77                     | 90                    | 9                           | 129   | 200   |
| 8                           | 84                     | 97                    | 10                          | 129   | 220   |
| 9                           | 91                     | 105                   | 11                          | 131   | 240   |
| 10                          | 98                     | 105                   | 12                          | 135   | 260   |

*From Hanna [22]. † Grams (dry weight) per 100 L.

This study consisted of two treatments: aquaculture effluent (AE) and commercial fertilizer (CF). AE was pumped from the irrigation sump adjacent to the fish greenhouse. The tomato varieties were evaluated simultaneously but in separate experiments. Plants were arranged in a completely randomized design, with 10 replicates for both treatments of “Favorita”. “Goldita” had 9 replicates of AE-grown plants and 11 replicates of CF-grown plants. Tomato harvest began 61 days after transplanting (DAT), and fish harvest occurred at 117 DAT of the tomato crop. Tomato harvest continued daily until the termination of the study (157 DAT). Tomato fruits were harvested based on ripeness, with fruit color used as an indicator. Tissue samples were taken at the final harvest.

The irrigation sump was used to access clarified water for the drip irrigation system for the soilless culture of cherry tomatoes in the adjacent greenhouse. A 1118.5 W (1.5 horsepower) irrigation pump was plumbed to the previously described irrigation sump, where it drew AE water from ⅓ the depth of the tank and delivered pressurized settled water at 206.8 kPa (30 psi) to the tomato irrigation system (Figure 1). The pressure was regulated by bleeding excess pressure back into the irrigation sump. Both treatments were delivered to plants using a clog-resistant pressure-compensated emitter (Bowsmith Nonstop Emitter, Bowsmith Inc. Exeter, CA, USA) at a flow rate of 3.785 L·h⁻¹. Each container was outfitted with two emitters. Plants grown with AE received water directly from the irrigation sump. Plants grown with CF received water and fertilizer through 2 fertilizer injectors (Model DM11, Dosatron, Clearwater, FL, USA). This allowed separate, but simultaneous, injections of the hydroponic fertilizer blend and calcium nitrate. Solenoid valves responsible for delivering the respective treatments were wired in tangent so that both treatments were applied at the same time.
A three-liter sample of the fish culture water and AE from the irrigation sump was collected and analyzed once weekly to characterize total ammonia nitrogen (TAN), nitrate, nitrite, potassium, and orthophosphate of the water being used to irrigate the tomato plants receiving AE. Each sample was filtered using a 40-micron Whatman™ glass fiber filter (VWR International, Radnor, PA, USA). Standard curves were fit for TAN, nitrate–nitrogen, potassium, and orthophosphate on a GENESYS 20 visible spectrophotometer (Spectronic Unicam, Rochester, NY, USA). Nessler method 8038 (Hach Company, Loveland, CO, USA) was used to determine TAN; the ascorbic acid method 8048 (Hach Company, Loveland, CO, USA) was used to determine orthophosphate. Nitrate–nitrogen and potassium were analyzed using Cardy twin nitrate and potassium meters (Spectrum Technologies, Inc., Plainfield, IL, USA). Titration method 8329, using ethylenediamine–tetraacetic acid (Hach Company, Loveland, CO, USA), was used to determine calcium and magnesium. Total phosphorus and total nitrogen were determined through persulfate digestion [23]. Digestates of nitrate and orthophosphate were determined using spectrophotometric screening and an ascorbic acid method [23–25].

Plant tissue was collected at termination from the third leaf from the terminal shoot. Samples were analyzed at Brookside Laboratories (New Bremen, OH, USA) for N. Combustion analysis was used to determine total nitrogen [26] using a Carlo Erba 1500 series analyzer (CE Elantech, Inc., Lakewood, NJ, USA). Minerals (P, K, Ca, Mg, S, B, Fe, Mn, Cu, Zn, and Al) were extracted using methods described by [26] and analyzed with a Thermo 6500 duo ICP (Thermo Fisher Scientific, Inc., Waltham, MA, USA).

Settleable solids were determined for water contained in the fish tank and water returning to the tank from the irrigation sump using an adopted procedure of Standard Method 2540 F [23]. Avliminech [27] reported that floc particles became reanimated if left undisturbed for the 1-h recommended settling time in the procedure described in Standard Method 2450 due to gas bubbles forming. For purposes of this study, a 30-min period was used for settling. Suspended solids were measured according to Standard Method 2540 D [23] using glass fiber filtration, followed by gravimetric analysis. The pH of AE of the samples was taken twice daily at approximately 9:00 a.m. and 4:00 p.m.

An analysis of variance was performed on all responses using a generalized linear model (PROC GLIMMIX in SAS version 9.4 SAS Institute, Cary, NC, USA). The experimental design for yield was a randomized design, with each variety analyzed separately. Due to a mistake at planting, the varieties were not randomized together; thus, no comparisons are made between varieties. The treatment design for yield was a two-way factorial of nutrient source and harvest date. Data recorded over harvest dates were analyzed as repeated measures using a heterogeneous compound symmetry covariance structure. Linear and quadratic trends were tested using qualitative/quantitative model regressions, and differences between fertility types least squares means were tested using F-tests. The experimental design for two yield totals (pre and post fish harvest) was a completely randomized design. Differences in yield between fertility types and between yield totals at fish harvest and
termination were tested using F-tests. Where residual plots and a significant covariance test for homogeneity ($H_0 = $ homogeneity) indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity.

Means comparisons for plant tissue were analyzed using a $t$-test (Proc TTest SAS, ver. 9.2, SAS Institute, Cary, NC.). If variances were equal, the pooled method was used to determine significance. If variances were unequal, the Satterthwaite method was used to determine significance.

3. Results

3.1. Fish Production

Fish were grown in the biofloc system for 149 days. The final harvested biomass was 1502 kg (15.0 kg/m$^3$) live weight of tilapia (Table 2). The total harvested fish biomass produced (final–initial) was 1032 kg of fish (10.3 kg/m$^3$; Table 2). Survival was approximately 96%, with 3000 fish stocked and 2872 fish harvested. This yield represents a 220% increase in growth over 149 days of production, and fish grew at a rate of 2.3 g/day/fish.

| Table 2. Inputs and outputs of a 149-day tilapia crop in a 100-m$^3$ production system. |
|-----------------------------------------------|-----------------|-----------------|-----------------|
|                                               | Total per 100 m$^3$ | per m$^3$ of Fish Production | per kg of Fish |
| Final Biomass (kg) $^\text{Y}$                | 1502            | 15.0            | -               |
| Beginning biomass (kg)                        | 470             | 4.7             | -               |
| Feed (kg)                                      | 2010            | 20.1            | 1.9             |
| Power use (kWh) $^\text{X}$                   | 5338            | 53.4            | 5.2             |
| Water (m$^3$)                                  | 168             | 1.7             | 0.2             |
| Base (kg) $^\text{W}$                         | 159             | 1.6             | 0.2             |

$^\text{Z}$ Calculated from 100 m$^3$ fish production unit. $^\text{Y}$ Final biomass of Nile tilapia (*Oreochromis niloticus*) and 96% survival rate. $^\text{X}$ Power included energy consumption from regenerative blowers and greenhouse fans. $^\text{W}$ Calcium hydroxide was used as base source.

The biofloc system used in this study was managed strictly as an autotrophic system with no supplemental carbon inputs. Water exchange was minimal and typically only involved make-up water due to loss from solid removal and plant water needs. Total water use was approximately 168 m$^3$ and translated to 6.14 kg/m$^3$ per kg of fish biomass produced (total water use/fish biomass produced; Table 2). The power required was 5.2 kW/kg of tilapia biomass produced and translated to 35.8 kW/day (Table 2). Base addition using calcium hydroxide would be considered a minor input of 158.9 kg or 0.2 kg per kg of fish biomass gained. Feed inputs totaled 2010 kg (20.1 kg/m$^3$) and represented an FCR of 1.9 (Table 2).

Total ammonia nitrogen was averaged to 2.3 ± 0.95 mg/L in the fish production tanks (Table 3). The mean nitrite within fish production tanks was 6.2 ± 1.5 mg/L, above recommended levels. Dissolved oxygen (DO) concentrations averaged 5.7 to 4.9 mg/L for morning and afternoon, respectively (Table 4). DO concentrations were approximately 16% higher in the morning than in the evening (Table 4). The difference observed in the mean temperatures, between morning (26.9 °C) and afternoon (27.8 °C), in combination with feed inputs, were likely the reason for DO temperature fluctuations. Water pH within the fish culture tank was maintained at approximately 6.7 (Table 4).
Table 3. Water quality parameters as related to fish health during the 149-day production cycle in the minimum water exchange biofloc production system.

| Parameter               | Location        | Mean ± Standard Deviation |
|-------------------------|-----------------|----------------------------|
| Total Ammonia Nitrogen  | Production Tank | 2.3 ± 0.95                 |
|                         | Exiting Clarifier | 2.2 ± 1.15               |
| Nitrite (mg/L)          | Production Tank | 6.2 ± 1.50                 |
|                         | Exiting Clarifier | 6.1 ± 1.30               |
| Nitrate-N (mg/L)        | Production Tank | 330.6 ± 99.70              |
|                         | Exiting Clarifier | 331.0 ± 106.00           |
| Total Hardness (mg/L)   | Production Tank | 1217 ± 368.00              |
|                         | Exiting Clarifier | 1232 ± 368.00           |
| Total Suspended Solids  | Production Tank | 508.8 ± 210.00             |
|                         | Exiting Clarifier | 463.6 ± 170.60           |
| Settleable Solids (ml/L)| Production Tank | 21.1 ± 21.60               |
|                         | Exiting Clarifier | 11.6 ± 15.90            |

*Z: Standard deviations of the means were calculated from water samples taken weekly.*

Table 4. Daily water quality parameters as related to fish health in the minimum water exchange biofloc production system.

| Parameter               | Time Measured | Mean ± Standard Deviation |
|-------------------------|---------------|----------------------------|
| Dissolved Oxygen (mg/L) | AM            | 5.7 ± 0.8                  |
|                         | PM            | 4.9 ± 0.5                  |
| Temperature (°C)        | AM            | 27 ± 3.0                   |
|                         | PM            | 28 ± 3.0                   |
| pH                      | AM            | 6.7 ± 0.2                  |
|                         | PM            | 6.7 ± 0.2                  |

*Z: Standard deviations of the means were calculated from weekly water samples.*

3.2. Cherry Tomato Production

For tomato production before fish harvest (117 DAT), few differences in yield were observed between plants grown with AE and CF for each harvest date for the cherry tomato ‘Favorita’ (Tables 3, 5 and 6). Some differences were seen between treatments before fish harvest in ‘Goldita’ (Table 6). At fish harvest, the total yields across all harvest dates for ‘Favorita’ were 5.9 kg/m² (CF) and 5.5 (AE) kg/m² and were not different (Table 7). However, for ‘Goldita’, yields were 5.5 kg/m² (CF) and 4.3 kg/m² (AE) kg/m² and were significant (Table 7). The fish production system went 22 days without feed input until a new crop of fish was stocked. At crop termination, differences in total yield were observed between AE and CF and were higher for CF-grown plants. Total yield at tomato crop termination (157 DAT) for ‘Favorita’ was 11.4 kg/m² for CF-grown plants and 9.3 kg/m² for AE-grown plants (Table 7). ‘Goldita’ plants produced 10.54 kg/m² of fruit for CF-grown plants and 7.4 kg/m² for AE-grown plants (Table 7).
Table 5. Probability values from analysis of variance for yield, shown by cultivar and harvest date.

| Cultivar | Yield by Harvest Date | Total Yield |
|----------|-----------------------|-------------|
|          | ANOVA Pr > F          | ANOVA Pr > F |
| Cv. Goldita | Nutrient Source <0.0001 | Nutrient Source <0.0001 |
|           | Harvest Time <0.0001   | Harvest Time (117 and 157 days) <0.0001 |
|           | Nutrient Source × Harvest Time <0.0001 | Nutrient Source × Harvest Time 0.0006 |
| Cv. Favorita | Nutrient Source <0.0001 | Nutrient Source 0.0013 |
|           | Harvest Time <0.0001   | Harvest Time (117 and 157 days) <0.0001 |
|           | Nutrient Source × Harvest Time <0.0001 | Nutrient Source × Harvest Time 0.0172 |

Table 6. Fertility type influence on yield by harvest date and variety.

| Cultivar | Yield by Harvest Date (kg·m²) by Harvest Time* |
|----------|-----------------------------------------------|
|          | DAT 59 67 73 80 88 98 105 116 130 141 150 157 Sign. |
| Cv. Goldita | CF x 0.1 0.5 0.7 0.4 0.6 1.4 0.9 1.2 1.2 1.2 1.2 Q*** |
|           | AE x 0.1 0.5 0.6 0.4 0.7 1.4 1.0 0.8 1.0 0.8 0.8 Q*** |
| Significance | ns * * ns ns ns * * * * * |
| Cv. Favorita | CF x 5.5 10.5 * CF 5.9 11.4 * |
|           | AE x 4.3 7.4 * AE 5.5 9.3 * |
| Significance | * * | Sign. ns |

*Nutrient source by harvest date interaction was significant at p < 0.05 (*). Y Significant quadratic (Q) trends using qualitative/quantitative model regressions at p < 0.001 (***). x CF = Conventional fertilizer treatment. W AE = Aquaculture effluent treatment. Y Least squares means comparisons between fertility types using F-tests at p < 0.05. ns = not significant.

Table 7. Nutrient source influence on total yield at fish harvest (117 DAT) and crop termination (157 DAT).

| Cultivar | Yield at Fish Harvest | Yield at Termination | Sign. | Yield at Fish Harvest | Yield at Termination | Sign. |
|----------|-----------------------|----------------------|-------|-----------------------|----------------------|-------|
| Goldita       | CF x 5.5             | 10.5                | *     | CF 5.9                | 11.4                | *     |
|           | AE x 4.3             | 7.4                 | *     | AE 5.5                | 9.3                 | *     |
| Sign.       | *                    | *                   |       | Sign.                | ns                  |       |

* Nutrient source by harvest date interaction was significant at p < 0.05 (*). Y Least squares means comparisons between fertility types (columns) and harvest date totals (rows) using F-tests at p < 0.05 (*). ns = not significant.

X CF = Conventional fertilizer treatment. W AE = Aquaculture effluent treatment.

ANOVA was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design for yield was a completely randomized design with each cultivar analyzed separately.
3.3. Aquaculture Effluent Nutrient Parameters

Macronutrients were only recorded up to fish harvest, with the exception of one sample analyzed at the termination of the tomato crop (Table 8). Nitrate–nitrogen was considerably higher for AE when compared to CF throughout the study and ranged from 150 to 540 mg/L. At crop termination, nitrate–nitrogen was 4 times the concentration in AE than CF. Available phosphorus was considerably lower for AE than CF and likely influenced yield. Concentrations of PO$_4$-P in AE ranged from 7 to 25 mg/L and averaged 14 mg/L for AE and 60 mg/L for CF in the last 9 weeks of production. The supply of K was adequate for plant growth throughout the study. As a result of daily additions of CaOH to maintain pH and the minimum exchange of water, calcium was in excess for AE throughout the entire study and ranged from 184 to 688 mg/L. At termination, AE had 3 times as much Ca when compared to the CF treatment. Magnesium ranged from 24 to 71 mg/L but was typically within ranges found in common nutrient solutions [28].

Table 8. Macronutrient concentrations for aquaculture effluent and conventional fertilizer treatments used to grow cherry tomato.

| DAP   | NO$_3$-N | PO$_4$-P | Total P | K   | Ca | Mg |
|-------|----------|----------|---------|-----|----|----|
| CF YX | AE       | CF       | AE      | AE  | AE | CF |
| 5     | 60       | 150      | 26      | 17  | 60 | 108 |
| 12    | 73       | 170      | 29      | 17  | 39 | 125 |
| 19    | 88       | 210      | 34      | 17  | 65 | 144 |
| 23    | 101      | 250      | 38      | 16  | -  | 161 |
| 33    | 116      | 250      | 43      | 13  | 82 | 181 |
| 41    | 128      | 300      | 46      | 10  | 81 | 197 |
| 47    | 131      | 320      | 51      | 7   | 60 | 217 |
| 54    | 133      | 340      | 55      | 11  | 77 | 233 |
| 61    | 135      | 340      | 60      | 8   | 70 | 253 |
| 68    | 135      | 360      | 60      | 11  | 68 | 253 |
| 80    | 135      | 400      | 60      | 9   | 52 | 253 |
| 83    | 135      | 430      | 60      | 10  | -  | 253 |
| 89    | 135      | 370      | 60      | 21  | 74 | 253 |
| 86    | 135      | 440      | 60      | 13  | -  | 253 |
| 103   | 135      | 460      | 60      | 14  | -  | 253 |
| 110   | 135      | 520      | 60      | 25  | 90 | 253 |
| 152   | 135      | 540      | 60      | 12  | -  | 253 |

DAP = Days after planting. CF = Conventional fertilizer treatment. AE = Aquaculture effluent treatment.

Table 8 continued.

3.4. Nutrient Concentrations in Cherry Tomato Tissue

No visual symptoms of nutrient deficiencies were observed throughout the study. Leaf tissue concentration of nutrients at crop termination was generally lower for AE plants when compared to CF for both cultivars (Tables 9 and 10). For “Favorita”, no difference was observed in N tissue concentration between nutrient sources. “Goldata” plants grown with CF were higher in N concentrations when compared to AE. Calcium was significantly higher in AE-grown plants, across varieties, by a factor of 1.5. Sulfur, zinc, and aluminum were lower in leaf nutrient concentrations for AE when compared to CF with Favorita. Nutrients were generally lower for all elements in AE Goldita plants when compared to CF, with the exception of zinc and calcium.
Table 9. Nutrient concentration of cherry tomato “Favorita” leaf tissue.

| Treatment | Percent Macronutrient Found in Leaf Tissue Z (%) | Nitrogen | Phosphorous | Magnesium | Potassium | Calcium | Sulfur |
|-----------|-------------------------------------------------|----------|-------------|-----------|-----------|---------|--------|
| CF Y      |                                                 | 2.77     | 0.44        | 0.51      | 4.48      | 3.89    | 1.92   |
| AE X      |                                                 | 2.62     | 0.27        | 0.33      | 3.20      | 6.01    | 1.97   |
| Significance |                                               | NS       | *           | *         | *         | NS      | NS     |

| Treatment | Concentration (mg/L of micronutrient found in leaf tissue Z) |
|-----------|--------------------------------------------------------------|
| Boron     | Iron | Manganese | Copper | Zinc | Aluminum |
| CF        | 113.30 | 115.00   | 711.30 | 11.90 | 33.50    | 16.10   |
| AE        | 49.67  | 73.00    | 243.00 | 6.07  | 38.13    | 21.33   |
| Significance |                                               | *        | *       | *      | NS      | NS      | NS     |

Z. Means were analyzed using Proc T-test (SAS Version 9.2 SAS Institute, Cary, NC). If variances were found to be equal the Pooled method was used to determine significance. If variances were unequal Satterthwaite method was used to determine significance. p ≤ 0.05 (*); NS = nonsignificant. Y CF = Conventional fertilizer treatment. X AE = Aquaculture effluent treatment.

Table 10. Nutrient concentration of cherry tomato “Goldita” leaf tissue.

| Treatment | Percent Macronutrient Found in Leaf Tissue Z (%) | Nitrogen | Phosphorous | Magnesium | Potassium | Calcium | Sulfur |
|-----------|-------------------------------------------------|----------|-------------|-----------|-----------|---------|--------|
| CF Y      |                                                 | 2.93     | 0.31        | 0.78      | 4.87      | 4.35    | 1.99   |
| AE X      |                                                 | 2.63     | 0.23        | 0.47      | 3.33      | 6.41    | 1.61   |
| Significance |                                               | *        | *           | *         | *         | NS      | NS     |

| Treatment | Concentration (mg/L of micronutrient found in leaf tissue Z) |
|-----------|--------------------------------------------------------------|
| Boron     | Iron | Manganese | Copper | Zinc | Aluminum |
| CF        | 145.67 | 126.67   | 736.33 | 10.63 | 28.80    | 22.13   |
| AE        | 38.43  | 56.87    | 179.33 | 5.20  | 65.23    | 14.33   |
| Significance |                                               | *        | *       | *      | *       | *       | *      |

Z. Means were analyzed using Proc T-test (SAS Version 9.2 SAS Institute, Cary, NC). If variances were found to be equal the Pooled method was used to determine significance. If variances were unequal Satterthwaite method was used to determine significance. p ≤ 0.05 (*); NS = nonsignificant. Y CF = Conventional fertilizer treatment. X AE = Aquaculture effluent treatment.

Nitrogen in AE and CF plants, for both varieties, were lower than levels recommended by Snyder [29] (Table 11), with 4.0% to 5.5% N. However, it was found to be within ranges proposed by Jones [28] (2.5% to 4.0%). Phosphorus was lower for AE-grown Favorita and Goldita plants and was also below concentrations proposed by Snyder [29]. Magnesium was lower for AE-grown plants, across both varieties, and was also lower than levels recommended by Snyder [29] but were near the lower end of recommendations suggested by Jones [28]. For both varieties, potassium was lower than the level recommended by Snyder [29] for AE-grown plants. Potassium leaf nutrient sufficiency ranges were considerably lower (1.25% to 2.5%) than recommended by Snyder [28], and K tissue concentrations for AE plants were above this level for varieties. Calcium was significantly higher for AE plants when compared to CF-grown plants. No differences were seen in S tissue concentrations between the two treatments for Favorita, but S was slightly lower in AE-grown Goldita plants when compared to CF. Across treatments and varieties, S was above the recommended levels proposed by Jones [28].
Table 11. Optimum levels of nutrient elements in greenhouse tomato leaf tissue.

| Percent Macronutrient Found in Leaf Tissue | Snyder | Jones |
|-------------------------------------------|--------|-------|
| Nitrogen                                  | 4.0–5.5| 2.8–4.5|
| Phosphorus                                | 0.3–1.0| 0.3–0.75|
| Potassium                                 | 4.0–7.0| 2.5–4.0|
| Calcium                                   | 1.0–5.0| 1.5–4.0|
| Magnesium                                 | 0.4–1.5| 0.4–1.3|

Concentration (mg/L) of micronutrient found in leaf tissue

| micronutrient | Snyder | Jones |
|---------------|--------|-------|
| Iron          | 100–250| 40–300|
| Zinc          | 30–150| 20–100|
| Manganese     | 40–300| 40–400|
| Copper        | 5–25   | 20-May|
| Boron         | 35–100 | 25–100|
| Molybdenum    | 0.15–5.0| 0.1–10|

\(Z\) From Snyder (1992) and Jones (2005).

Differences between treatments and micronutrients were substantially greater than what was observed in the macronutrients. Boron was within sufficiency ranges but were 56% and 73% lower in AE tissue when compared to CF for Favorita and Goldita, respectively [29]. AE-grown plants were 27% (“Favorita”) and 55% (“Goldita”) lower than CF-grown plants and were below the suggested levels of Snyder [29] but within the acceptable levels of Jones [28]. Sufficiency ranges for Mn have a wide range, and AE plants for both varieties fell within these ranges; however, they were 65% (“Favorita”) and 75% (“Goldita”) lower than CF tissue concentrations. Copper for AE-grown plants was within sufficiency ranges, but at the lower end, and was nearly half of the concentrations in CF-grown plants. No differences were seen in Zn tissue between treatments for Favorita, but AE-grown Goldita plants contained nearly twice the amount of Zn in AE plants when compared to CF.

4. Discussion

4.1. Fish Production Parameters

The biomass load in this study (15.0 kg/m³) is comparable to that in the study of Rakocy et al. [30], with a similarly managed outdoor system (14.4 kg/m³ and 13.7 kg/m³) and similar tank volume and horsepower aeration (0.56 kW/100 m³). Timmons and Ebeling [31] described 40 kg/m³ as the maximum biomass that can be produced through aeration with no supplemental oxygen. Growth rates for biofloc tilapia production (2.3 g/day/fish) were lower than reported by Rakocy et al. [30] (3.0 to 4.0 g/day/fish). FCRs in this experiment were comparable to FCR reported by Rakocy et al. [30] of 2.2 to 1.8 g of feed to grams of net fish biomass. Reduced growth rates could be due to chronic high nitrite concentrations experienced throughout production. It was observed that the fish response to feed was less aggressive; however, mortality remained less than 4% throughout the production cycle. Total ammonia nitrogen averaged to 2.3 ± 0.95 mg/L in the fish production tanks (Table 3). The mean nitrite within fish production tanks was 6.2 ± 1.5 mg/L, above recommended levels. Dissolved oxygen (DO) concentrations averaged 5.7 to 4.9 mg/L for morning and afternoon, respectively (Table 4). DO concentrations were approximately 16% higher in the morning than in the evening (Table 4). The difference observed in mean temperatures between morning (26.9 °C) and afternoon (27.8 °C), in combination with feed inputs, was likely the reason for DO temperature fluctuations. Water pH within the fish culture tank was maintained at approximately 6.7 (Table 4).

4.2. Tomato Production

This study shows the potential for the integration of BFT and hydroponic cherry tomato production, but improvements are necessary to increase yield. The control (conventional fertilizer) used in this study was comparable to yields reported in the literature [32,33]. Testa et al. [33] reported yields from 30 cherry tomato greenhouse operations in Sicily. The Sicilian growers used “Creative F1”, had an average plant density of 3.2, and carried crops to the 20 and 22 fruit clusters. In our study, “Favorita”
plants grown with AE were near the lower end of the range reported by Testa [33] when comparing the calculated yield per fruit cluster. Nevertheless, AE-grown “Favorita” yields from our study were considerably lower than those reported by Halmann and Kobryn [32] when comparing the calculated yield per fruit cluster.

Reduced yield in AE-grown plants was likely a result of plant nutrition. Plants grown with AE were generally lower in concentrations of nutrients in leaf tissue; however, no symptoms of deficiency were visually observed throughout the study (Tables 9 and 10). Phosphorus concentrations may have been the most limiting nutrient as AE-grown plants were 26% (“Goldita”) and 30% (“Favorita”) lower in P than CF-grown plants. Phosphorus concentrations in tissue were also found to be below the recommendations reported by Snyder [29]. Available phosphorus was in undersupply throughout the study (Table 8); however, this did not explain the distinction in yield difference pre and post fish harvest. Supraoptimal Ca concentrations due to twice daily calcium hydroxide applications could have influenced the availability of P. Calcium phosphate formation would have been intensified if pH increased within the irrigation system or pore water within the substrate, but pH was not measured in these areas.

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Excessive Ca concentrations may have resulted in lower available P. In a later study using the same system, Blanchard et al. [34] investigated the response of pH on nutrient assimilation of nutrients in aquaponically grown cucumbers; however, Ca concentrations were considerably lower than levels observed in this study. Da Cerozi and Fitzsimmons [34] demonstrated the effects of pH on P availability; however, a significant reduction was not realized until pH reached 10. In this same study, Ca-binding compounds (dissolved organic carbon and alkalinity) were determined to play a significant role in preventing mineralization of orthophosphate. These compounds bind to available Ca, thereby reducing the opportunity for calcium phosphate formation [35]. In our study, Ca was in plentiful supply while alkalinity was low (data not shown). Dissolved organic carbon was not measured. More work is needed to determine if increasing the availability of P through pH modification in a similar situation, with extreme Ca availability, would increase yield.

Many of the macronutrients (N, P, K, and Mg) were found to be lower in AE-grown plants despite concentrations being greater than the recommended levels. We speculate that denitrification may have occurred in the irrigation systems due to anaerobic conditions associated with the hydraulic retention time between irrigation cycles. Denitrification would reduce nitrate in the system and, subsequently, increase pH. The case for denitrification could be made as NO\textsubscript{3} concentrations were 4 times greater in AE when compared to the CF solution, yet AE was found to have lower concentrations in tissue than CF. Water samples used in the analysis were taken at the irrigation sump instead of the drip emitter; consequently, it cannot be determined if nutrient concentration or availability changed between the irrigation sump and the drip emitter.

5. Conclusions

This study demonstrates that substrate-based hydroponic systems have the potential to be integrated with biofloc production systems. However, further refinements are needed to increase yields to commercial levels. Future work in decoupled systems should investigate the potential for denitrification occurring in the drip irrigation system. Evaluation of alternatives to CaOH for pH management in the system may also improve the yield of fruiting crops grown with BFT effluent by reducing free Ca in the system.

Author Contributions: Conceptualization, J.M.P., J.J.D., J.L.S., J.A.C., and T.R.H.; methodology, J.M.P.; formal analysis, J.M.P.; data curation, J.J.P. and J.J.D.; writing—original draft preparation, J.M.P.; writing—review and editing, J.M.P., J.L.S., J.A.C., and T.R.H.; visualization, J.M.P.; supervision, J.M.P.; project administration, J.A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Soy Aquaculture Alliance and Alabama Agriculture Experiment Station.

Acknowledgments: The authors wish to thank Raymond Kessler for his assistance with data analysis and Luke Foshee and Micah Fern in their assistance with data collection and project maintenance.

Conflicts of Interest: The authors declare no conflict of interest.
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